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A RIGOROUS METHOD FOR COMPUTING GEODETIC DISTANCE FROM SHORAN OBSERVATIONS

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Abstract--This paper presents a theoretically accurate method of computing geodetic distances from shoran observations and then demonstrates a method of close approximation by numerical integration.

The problem of obtaining geodetic distance from shoran observations depends, essentially, on four given conditions: (1) The altitude, H, of the airborne station; (2) the altitude, K, of the ground station; (3) the time, t, required for the shoran ray to travel from the airborne station to the ground station; and (4) knowledge of the meteorological conditions which affect the velocity and direction of the shoran ray.

The solution to the problem rests on the following basic assumptions:

(1) The figure of the Earth is represented by the International Sphere, whose radius, R, is 6,371,227 m.

(2) The shoran ray lies in a plane which passes through the center of the Earth. The geodesic distance is the intersection of this plane with the surface of the Earth, terminated by the two points on the Earth's surface lying directly beneath the ground station and the airborne station [ASLAKSON and RICE, 1946].

(3) The shoran ray is governed by the laws of geometric optics. Its velocity varies inversely as μ, the index of refraction, which is assumed to be numerically equal to the square root of the dielectric constant [MASSACHUSETTS INSTITUTE OF TECHNOLOGY, 1943].

(4) The velocity of light V is equal to Anderson's 1941 value of 299,776 km/sec.

The solution to the problem is approached by first establishing the relationship $r\mu \cos \alpha = k$, where r is the distance from the center of the Earth to a point on the ray path, μ is the index of refraction at the point, α is the complement to the angle of incidence i at the point, and k is a constant. Figure 1 represents a spherical Earth surrounded by infinitesimally thin layers of atmosphere having different values of μ. By the law of sines, $r'/\sin(180^\circ - i) = r/\sin e$. By using Snell's law, $\mu' \sin i' = \mu \sin e$, the above can be written as $r\mu \cos \alpha = r'\mu' \cos \alpha'$. Since this relationship holds between any two adjacent layers, it must be constant for all layers with respect to any particular path.

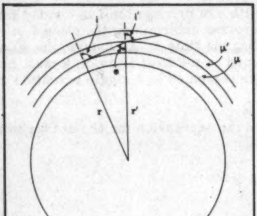

Fig. 1--Spherical Earth surrounded by infinitesimally thin layers of atmosphere

The theory of the solution itself is demonstrated by means of Figure 2. From the differential triangle constructed on the ray path, the following relations are apparent: $dr/dt = (V/\mu) \sin \alpha$ and $d\theta/dt = (V/r\mu) \cos \alpha$.

By using the relation $r\mu \cos \alpha = k$, the above become

$$dr/dt = (V/\mu)\sqrt{1 - k^2/r^2\mu^2}$$

$$d\theta/dt = Vk/r^2\mu^2$$

By Maclaurin's series

$$r_n = r_1 + t(dr/dt)_1 + (t^2/2)(d^2r/dt^2)_1 + \dots\dots$$

and

$$\theta = t(d\theta/dt)_1 + (t^2/2)(d^2\theta/dt^2)_1 + \dots\dots$$

where t is considered to be zero at the ground station and the derivatives are evaluated by letting $r = r_1$. If μ is considered as a function of r, any number of derivatives of r and θ with respect to t can be obtained.

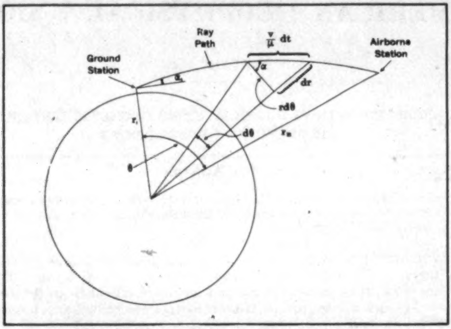

Fig. 2--Elements involved in the solution

The procedure used in obtaining geodetic distance by means of the above series is:

(1) From the meteorological data μ is set up as a function of r.

(2) An approximate value for k is found. This can be done by solving the triangle whose sides are $(4/3)r_1$, $(4/3)r_n$, and Vt in order to obtain α_n. Having obtained α_n, $k = r_n \mu_n \cos \alpha_n$.

(3) The r_n series is evaluated. If the result is in disagreement with the given r_n, k is adjusted proportionally and the series evaluated again. Usually the adjusted value of k is sufficiently accurate.

(4) The series for θ is evaluated and the geodesic distance is expressed as $R\theta$. At this point correction for the spheroidal shape of the Earth can be applied to produce the geodetic distance.

The above method is extremely laborious and therefore impractical. It has been used to compute one 298-mile arc, based on the special condition that α_1, the "take-off" angle from the ground station, is equal to zero. The method, however, is of theoretical value and is useful as a check against the method of numerical integration presented below.

When the problem is solved by numerical integration the time of propagation t is divided into small intervals of time, each equal to Δt. The method then involves determining the change in r during each of these intervals, and hence the total change during the time, t. As before, the solution depends on the proper choice of k. If the value r_n is not obtained on the first attempt, k must be adjusted until r_n is obtained. Then the total change in θ can be computed in a single operation as the sum of the changes occurring in each of the intervals Δt.

The key to the method of numerical integration is given in the expression for the change in r during the m^th^ time interval

$$r_{m+1} - r_m = \Delta t \int_0^1 (dr/dt)_{m+\epsilon}\, d\epsilon$$

After the application of finite difference techniques, the above can be written

$$r_{m+1} - r_m = 1.917\, q_m - 1.334\, q_{m-1} + 0.417\, q_{m-2}$$

where

$$q_m = \Delta t\, (dr/dt)_m = (V\Delta t/\mu) \sqrt{1 - k^2/r^2 \mu^2}$$

In a similar manner

$$\theta_{(m+1)} - \theta_m = Vk\Delta t\, (1.917\, p_m - 1.334\, p_{m-1} + 0.417\, p_{m-2})$$

where

$$p_m = 1/(r\mu)_m^2$$

The total value θ can be expressed as

$$\theta = Vk\Delta t\left[\sum_{i=1}^{n-1} p_i - 0.583\,(p_1 - p_3) + 0.417\,(p_5 - p_{n-2}) - 0.917\,(p_4 - p_{n-1})\right]$$

An illustration of the method is given in Table 1.

Table 1--Solution by numerical integration

r	μ	$10\,r^2\mu^2$	q	$p \times 10^{18}$
M ft				
20,902.99392	1.0003274	4,372,213,068	0.296134	2,287,171,244
20,903.29892	1.0003268	4,372,335,416	0.313869	2,287,107,243
20,903.62138	1.0003257	4,372,460,698	0.331044	2,287,041,712
20,903.96078	1.0003243	4,372,590,444	0.347937	2,286,973,849
20,904.31705	1.0003221	4,372,720,259	0.364057	2,286,905,955
20,904.68884	1.0003187	4,372,846,073	0.379024	2,286,840,157
20,905.07487	1.0003147	4,372,972,605	0.393503	2,286,773,987
20,905.47541	1.0003102	4,373,100,832	0.407651	2,286,706,935
20,905.89000	1.0003058	4,373,235,811	0.422031	2,286,636,356
20,906.31932	1.0003011	4,373,374,331	0.436296	2,286,563,931
20,906.76270	1.0002962	4,373,516,985	0.450515	2,286,489,348
20,907.22031	1.0002910	4,373,662,972	0.464613	2,286,413,028
20,907.69192	1.0002857	4,373,813,942	0.478756	2,286,334,109
20,908.17777	1.0002800	4,373,967,370	0.492713	2,286,253,910
20,908.67738	1.0002746	4,374,129,179	0.507016	2,286,169,336
20,909.19169	1.0002681	4,374,287,520	0.520634	2,286,086,581
20,909.71885	1.0002582	4,374,421,501	0.531883	2,286,016,562
20,910.25537	1.0002285	4,374,386,204	0.528961	2,286,035,008
20,910.77696	1.0002154	4,374,489,852	0.537552	2,285,980,843
20,911.32361	1.0002100	4,374,671,335	0.552267	2,285,886,009
20,911.88579	1.0002070	4,374,880,311	0.568736	2,285,776,819
20,912.46349	1.0002054	4,375,108,033	0.586153	2,285,657,845
20,913.05875	1.0002062	4,375,364,104	0.605136	2,285,524,076
20,913.67403	1.0002085	4,375,641,686	0.625061	2,285,379,087
20,914.30945	1.0002084	4,375,906,705	0.643506	2,285,240,677
20,914.96156	1.0002050	4,376,149,842	0.659976	2,285,113,710
20,915.62895	1.0001977	4,376,365,246	0.674234	2,285,001,237
20,916.30939			$R\,\theta$ = 100.4987176 miles	

In this example H was taken as 13,375 ft and K as 60 ft. The correct value for k was found to be 20907.46626. The values of μ were taken from a graph prepared from weather observations made along the ray path. The total time of propagation, 0.00054 sec, was broken into 27 intervals. That is, Δt was used as 0.00002 sec. Since the values for r_2 and r_3 were not obtainable from the relation $r_{m+1} - r_m = 1.917\,q_m - 1.334\,q_{m-1} + 0.417\,q_{m-2}$, these two values were gotten from an approximation to the Maclaurin series

$$r_2 = r_1 + q_1 + [(V\Delta t)^2/2r_1][r_1\,(d\mu/dr)_1 + 1]$$

and

$$r_3 = r_2 + q_2 + [(V\Delta t)^2/2r_2][r_2\,(d\mu/dr)_2 + 1]$$

Values for $d\mu/dr$ can be found simply and satisfactorily by a number of methods.

In a comparison of the numerical integration method with the series method as applied to the 298-mile line referred to above, there was found a difference of only 0.1 ft. This demonstrates that the method of numerical integration is sound. This agreement was expected, however, since the values of μ changed very smoothly throughout the path. On the other hand, should the values of μ fluctuate rapidly, the accuracy of numerical integration would vary with the size of the time intervals into which the path is broken.

When specially suitable atmospheres were considered it was found that approximation methods, based upon a fixed radius of curvature for the ray path, produce distances which are, for geodetic purposes, almost equivalent to those obtained by numerical integration. It was found, however, that the height of ray path varied considerably. On a particular 260-mile line there existed a maximum difference of almost a thousand feet. While in an ideal atmosphere a difference of hundreds of ft has little effect on the velocity of the shoran signal, it is conceivable that under unusual weather conditions the effect could be considerable. It is pointed out that the difference in distance obtained by approximate methods and the numerical integration method can be attributed almost entirely to the height of ray path and its resultant effect on velocity. The geometric effect of an incorrect radius of curvature is slight in comparison.

Although the method of numerical integration is not as short as the approximate shoran reduction formula now being used, it is worth noting that it consists almost entirely of an iteration process which could be carried out onelectronic computing equipment in a matter of a few seconds. It is believed that the accuracy gained would be worthwhile, especially in the case of long lines where unfavorable atmospheres are encountered.

Acknowledgments--The author's thanks and appreciation are extended to J. A. O'Keefe of the Army Map Service, for his advice and guidance in the planning of this paper, and to Mary Jane Camplair of the Army Map Service, for her excellent assistance in its preparation.

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SEISMIC REFLECTIONS FROM BENEATH THE OCEAN FLOOR

J. B. Hersey and Maurice Ewing

(Contribution No. 450 of the Woods Hole Oceanographic Institution)

Abstract--Apparatus and procedures are described with which seismic reflections have been obtained from the ocean bottom and from deeper horizons. The area surveyed lies between Bermuda, the Greater Antilles, and the United States. All records obtained in an east-west strip, 70 to 80 mi wide, extending from 61° W longitude south of Bermuda to 71° W longitude and thence southward as a strip 200 to 300 mi wide to about 23° N latitude, show a single prominent reflecting horizon at depths exceeding 500 ft below the bottom (assuming the seismic velocity in the bottom sediment to be equal to or greater than that of sea water). In this area the bathymetric data indicate that the bottom is either flat or relatively smooth. The records from other parts of the area are, with few exceptions, more complicated, correlating with bathymetric evidence of a rougher bottom there. A system is outlined for classifying reflection records obtained in deep water with suggested geologic significance of the various record types.

Introduction--During the period from September 1946 through June 1947, reflection observations have been made by the Woods Hole Oceanographic Institution's R/V Atlantis at 133 locations over 530,000 sq mi of the western Atlantic basin in the area bounded by lines from New York to Bermuda to Puerto Rico, by the Greater Antilles, the Bahamas, and the Eastern Coast of the United States. This report describes the instrumentation and procedures used and presents evidence that reflections were recorded from reflecting horizons below the ocean floor. Reflection records of different types were obtained depending on location. The correlation of these record types with submarine topography is discussed.

Instrumentation--The source of seismic energy was a pound of TNT exploded in the water at depths of the order of 100 to 300 ft in the earlier part of the work and depths of two or three ft in the later work. The detector was a Rochelle salt crystal hydrophone which fed an audio amplifier through a step attenuator and a Western Electric Type RA363 octave band pass filter. The amplifier has a flat response over the frequency range from 100 to 5000 cps. Oscillographic recordings were made by photographing a Dumont Type 208 oscilloscope with a 16 mm Bolex movie camera with its shutter and arresting mechanism removed to make it a strip camera. The film speed was approximately six inches per second. Timing marks were put on the film early in the work by a chronometer-controlled signal impressed directly on the input to the oscilloscope. Later the same timing signal was used to light a small neon bulb placed beside the oscilloscope tube.

Shooting procedure--All observations were made with the Atlantis hove to and the hydrophone lowered to depths varying from 150 to 1000 ft. The shallower depths were preferred throughout most of the work since the records were less complicated. Before a shot was fired the attenuator was set to avoid overloading on the direct shock wave. Shortly after the shot but before the first bottom reflection the attenuator was re-set manually for proper sensitivity to record the first bottom reflection. After it had been observed the attenuator might be re-set again for the second bottom reflection, and so on until no further reflected energy was observed. The time between reflections, about five to ten sec, was quite sufficient to make this adjustment, and usually the correct attenuator settings could be predicted from records of the previous location, even though the distance between stations was usually 60 mi.

At each location several shots were recorded using various settings of the octave filter. Since it is common experience in seismic prospecting for oil that very low sonic frequencies, 30 to 50 cps, are most useful in reflection work, low frequency records were attempted. In the early part of the work no useful records were obtained below the 150 to 300 cps band, so this and bands of higher frequency were used almost exclusively. Toward the end of the program an amplifier sharply tuned at 75 cycles gave good records in several areas.

The geometry of set-up as used through the early cruises led to an unnecessarily complicated record, but since considerable data were taken with this set-up, it is described. Since the shot

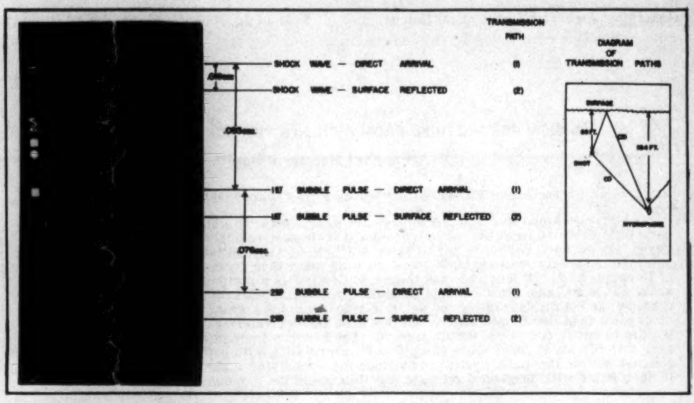
TRANSMISSION PATH
DIAGRAM OF TRANSMISSION PATHS
SHOCK WAVE — DIRECT ARRIVAL (1)
SHOCK WAVE — SURFACE REFLECTED (2)
.083sec.
1ST BUBBLE PULSE — DIRECT ARRIVAL (1)
1ST BUBBLE PULSE — SURFACE REFLECTED (2)
.076sec.
2ND BUBBLE PULSE — DIRECT ARRIVAL (1)
2ND BUBBLE PULSE — SURFACE REFLECTED (2)
SURFACE
66 FT.
(2)
164 FT.
SHOT
(1)
HYDROPHONE

Fig. 1--Sound from a deep shot recorded at short range

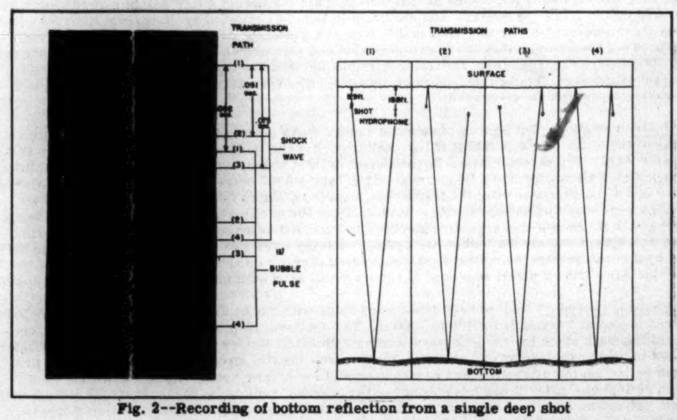
TRANSMISSION PATH
(1)
.051 sec.
(2)
(1)
(3)
SHOCK WAVE
(2)
(4)
(3)
1ST BUBBLE PULSE
(4)
TRANSMISSION PATHS
(1)
(2)
(3)
(4)
SURFACE
SHOT
HYDROPHONE
BOTTOM

Fig. 2--Recording of bottom reflection from a single deep shot

was located 100 to 300 ft below the surface, two shock waves normally went to the bottom; the direct shock, and its surface reflection. In addition to these, the first and second oscillations of the gas bubble of the explosion also sent out pulses. Since each was effectively double because of surface reflection a total of six readily resolvable energy pulses were reflected at the bottom. If the bottom has acted as a plane specular reflector and there has been no distortion of the pulses through the water, each pulse is detected in turn as it passes the hydrophone; each is also detected again after reflection at the surface. Thus if all pulses have sufficient intensity as many as 12 separate pulses may be recorded to represent the reflected energy from a single explosion after one bottom reflection. In practice it was found that generally either four or eight separate pulses were recorded These can be identified as coming from the direct shock, or the direct shock and the first oscillation of the gas bubble. Figure 1 shows a record of the direct and surface reflected pulses of a shot fired at a depth of 66 ft. Figure 2 shows an unusually clear record of a single bottom reflection.

In this case eight pulses are recorded. The reflection from a rough or inhomogeneous bottom would easily make this already complicated series of pulses hopelessly complicated and there would be little hope of interpreting the results in any detail.

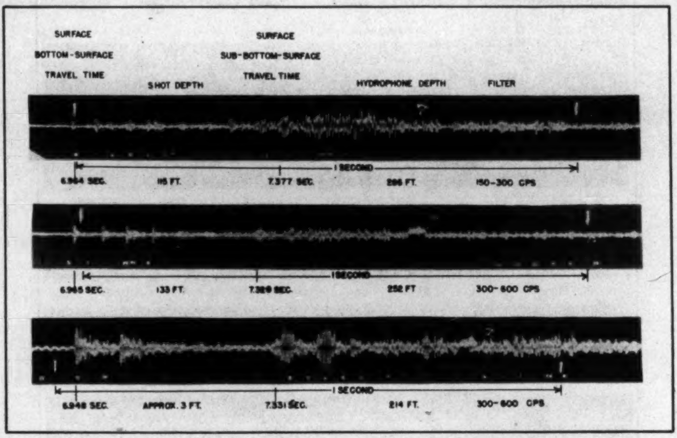

Fig. 3--Comparison of bottom reflections from deep and shallow shots

The apparatus and shooting procedure described are admittedly cumbersome and inadequate for studying bottom reflections. The fact that good recognizable reflections were obtained in certain localities must arise from the extreme simplicity of the structure of the bottom there and from the excellence of the water as an acoustical medium. In the course of the work some improvements were made both in instrumentation and shooting techniques which have improved the quality of the results, notably shooting at very shallow depths (less than three ft) so as to allow the explosion to blow out without oscillations of the gas bubble. This technique simplifies the signal due to a single reflection from a possible 12 pulses to two at most. Figure 3 presents a comparison of the two techniques showing the first bottom reflection for several shots at Station 4499 where both techniques were employed. Other developments such as (1) investigation of the frequency range below 100 cps, (2) use of multichannel recording, multiple detectors, and automatic volume control, and (3) a method of taking observations underway are being made as rapidly as possible, and can be expected to improve future results.

Bottom reflection data--If the ocean bottom were perfectly flat and homogeneous, a single sharp echo would be received from it. Where it is stratified, secondary reflections may be received due to reflection at surfaces beneath the bottom. Where it has topographic relief, secondary echoes may be obtained by side reflections from the topography. The principal criterion for deciding whether a given echo came from a side reflection from the bottom topography or from a reflection beneath the bottom was the frequency composition of the reflected sound. It was expected that passage through rock or sediment would attenuate the high frequencies more than the lows, as happens in seismic work on land.

The following is a summary of the evidence of reflection beneath the ocean bottom found in this study.

(1) Secondary reflections were observed in all cases.

(2) They were readily separable on the basis of frequency into those recorded at all frequencies, which are taken to be side reflections from bottom topography, and those recorded only at low frequencies, which are taken to come from below the bottom.

(3) Side echoes are prevalent in regions where the recording fathometer shows topographic relief.

(4) The most clear-cut sub-bottom echoes are found in the region which shows least topographic relief.

(5) At all stations over a large area, a single sub-bottom reflection was observed. The time lag of this reflection behind the bottom reflection varied in a continuous manner over the region, as would be expected if it represented reflection from an extensive sub-bottom surface.

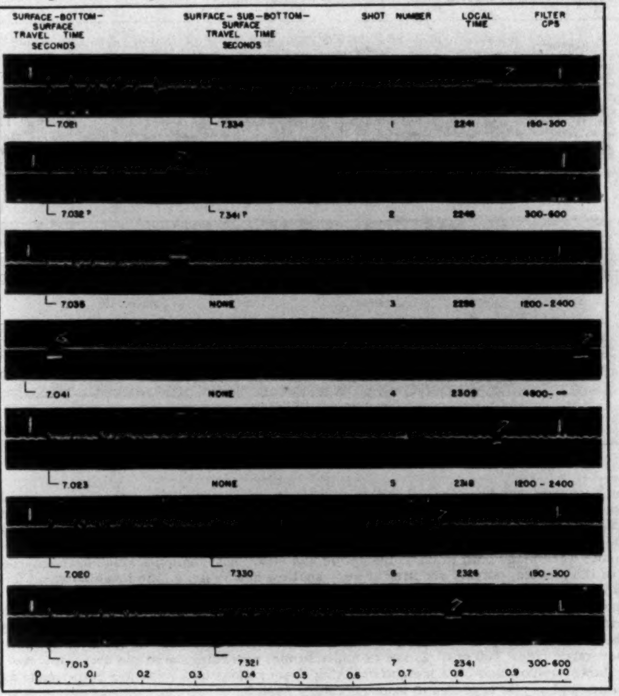

Fig. 4--Records of the first bottom reflections for all shots at Station 4498; type M records

To illustrate the principles of analysis, Figure 4 presents records in various frequency bands at Station 4498. At all frequencies there is a reflection at about 7.013 to 7.041 sec which corresponds to the ocean bottom. In the lower frequency records there is a later reflection at 7.321 to 7.341 sec which comes from a reflecting surface below the bottom. Two lines of evidence prove that the later reflection occurs at a continuous and more or less horizontal surface beneath the ocean bottom. (1) Over a large area these two reflections are obtained, and the time interval between them varies in a gradual manner. (2) The absence of high frequency sound in the later reflection is best explained by differential absorption within the bottom rocks.

The Swedish physicist, WEIBULL [1947], has reported similar bottom reflection studies in which secondary reflections were recorded. These were interpreted as coming from reflecting horizons below the bottom. His paper does not exhibit oscillograms of bottom reflections nor does it state how the secondary reflections are known to have penetrated the bottom sediments. Hence, it is difficult to compare the two investigations. However, from conversations with Weibull it is known that he did not make any frequency analysis of the reflected energy but demonstrated penetration by recording shots fired at radically different depths at the same location. The fact that

secondary reflections were recorded which showed the same time lag after the bottom reflections regardless of shot depth was taken as proof that they were reflected from an horizon below the ocean floor.

Record types--Records shown in Figure 4 form one of the principal types into which the records so far observed can be classified. In these the sub-bottom structure is extremely simple. The bottom reflection has an abrupt beginning and it is brief. The interval between the bottom and sub-bottom reflections is relatively quiet, and from the relative amplitudes of the bottom and sub-bottom reflections it is inferred that the acoustical contrast between the materials at the sub-bottom reflecting horizon is at least as great as that between the water and the bottom. The hypothesis is advanced that here remarkably homogeneous sediments overlie hard rock. Records of this general character are designated type M.

Two variations of type M have been observed. In both the bottom reflection begins sharply and is followed by a period of relative quiet before a simple sub-bottom echo. In one the amplitude of the bottom echo is less than half the sub-bottom echo, while in the other it is greater by at least a factor of two. These are designated, respectively, types L and N. Examples are shown in Figure 5. Examples of L, taken at Stations 4559 and 4560 were taken from shallow shots which, because they lack bubble pulses are readily interpreted. The example of N at Station 4505, taken from a deep shot, has all the complication of the bubble pulses and in addition it is probably further complicated by side reflections from bottom topography. For this reason a high frequency record at the same station is shown. Its complicated character compared with the high frequency records shown in Figure 4, for example, indicates topographic effects are present. However, there is no trace of the set of arrivals interpreted as sub-bottom reflections on the low frequency record. This is especially striking, since as a type N record the sub-bottom reflection has about twice the amplitude of the bottom reflection.

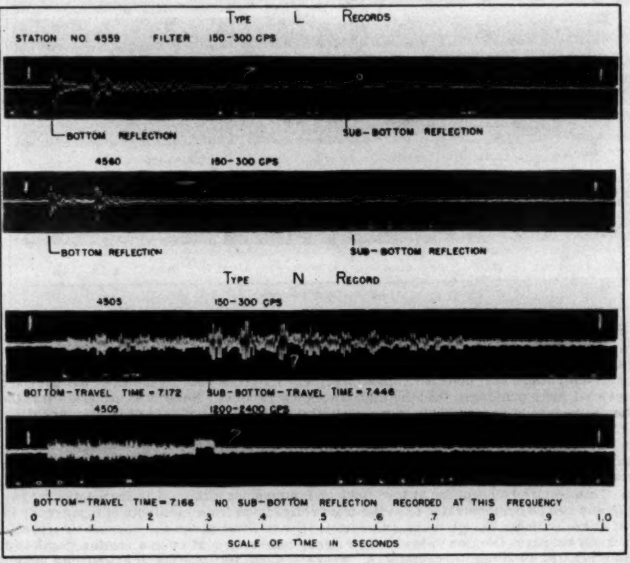

Fig. 5--Type L and N records

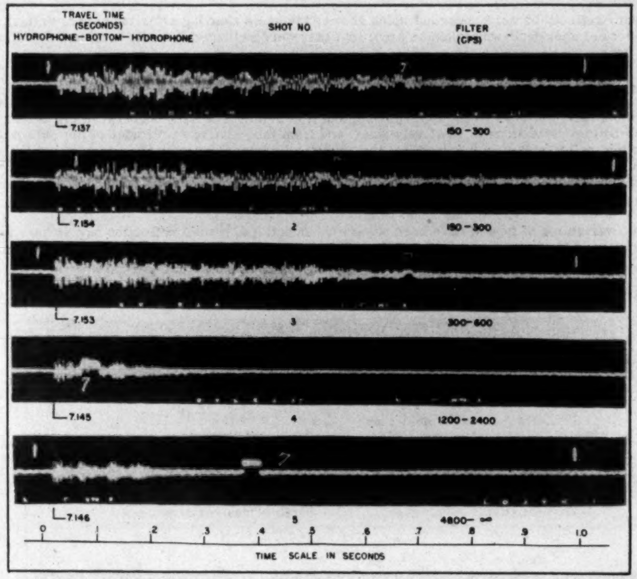

Fig. 6--Recordings of the first bottom reflection at Station 4504; type R records

At other locations such as Station 4504, shown in Figure 6, the lower frequency records show a complicated structure that does not repeat precisely from one shot to the next, but does appear to be somewhat more prolonged than the high frequency records. Here it is supposed that the sub-bottom structure is considerably more complicated. Records of this character are designated type R.

In some places, such as Stations 4483 and 4486, shown in Figure 7, the bottom reflection starts with a low amplitude forerunner followed shortly by a rather complicated group of high amplitude arrivals. This feature is recorded at low and high frequencies alike. It is frequently not reproducible and can be demonstrated to arise from reflections from elements of topography in the vicinity at some stations, though it seems possible that in some cases the correct interpretation may be a weak bottom reflection followed by a strong sub-bottom at such a shallow depth that all frequencies penetrate the bottom sediments. Where several frequencies are recorded simultaneously, it should be possible to decide between these two interpretations using differential absorption at different frequencies as a criterion for sediment penetration. Records of this character are called type F.

In still other cases such as Station 4502, shown in Figure 8, both low and high frequency records start abruptly and are very complicated. The several arrivals recorded on each are probably to be interpreted as reflections from various elements of topography in the vicinity. The method of recording used is at considerable disadvantage in that only one frequency band is recorded per shot and hence the travel-time relations are not maintained precisely for the various frequencies. Improved instrumentation on later cruises has produced records on which high and low frequency bands were recorded simultaneously. At some locations these records demonstrate that several arrivals later than the bottom reflection had not penetrated the bottom since they were clearly recorded on both high and low frequency traces. Records in which these characteristics predominate are called type T.

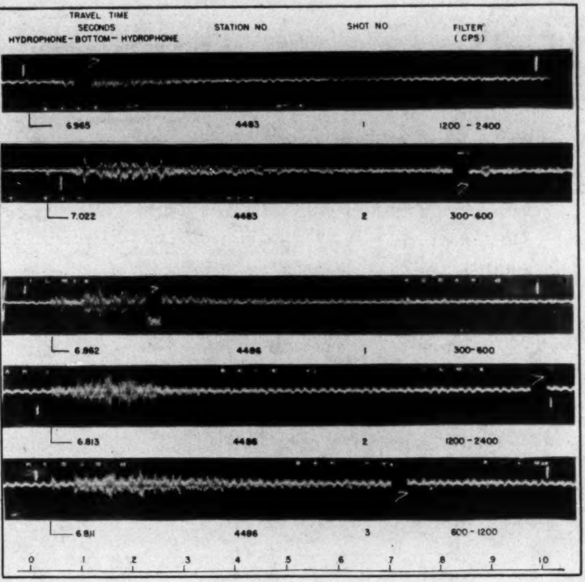

Fig. 7--Type F records

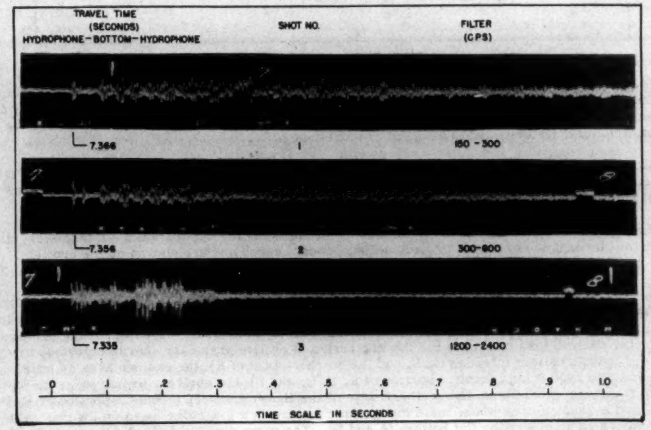

Fig. 8--Type T records

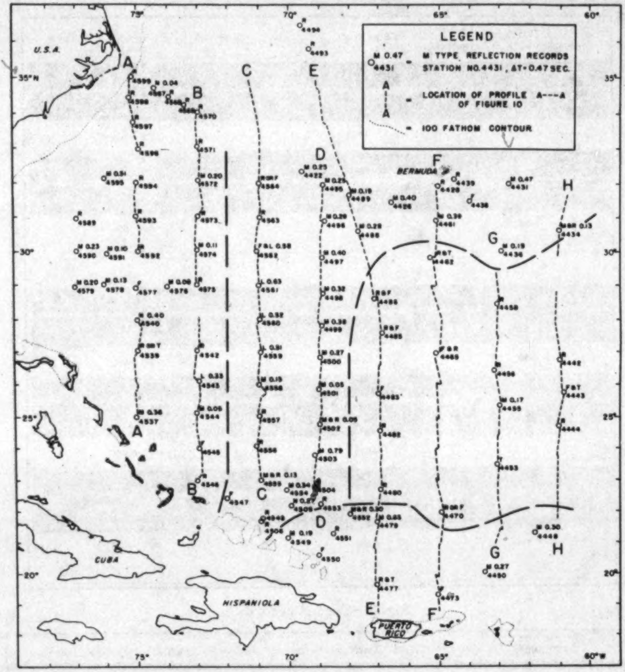
LEGEND
M 0.47 4431 - M TYPE REFLECTION RECORDS STATION NO.4431, ΔT-0.47 SEC.
A A - LOCATION OF PROFILE A---A OF FIGURE 10
- 100 FATHOM CONTOUR
U.S.A.
BERMUDA
CUBA
HISPANIOLA
PUERTO RICO
35°N
30°
25°
20°
75°
70°
65°
60°
60°W
A
B
C
D
E
F
G
H

Fig. 9--Chart of station locations and reflection-record types

Correlations with bottom topography--The area surveyed is shown in Figure 9. It is about 530,000 sq mi. Stations are at intervals of about 60 mi on lines about 100 mi apart. Naturally on so open a network of stations it is impossible to correlate from station to station except for the largest structural features and in areas of gradual change.

Over much of the area a continuous fathometer record was obtained, and over the rest of it sonic soundings were made at half-hour intervals. These data permit plotting the detailed profiles of submarine topography shown in Figure 10.

The legend of Figure 10 indicates the manner of obtaining the depth from the fathometer. Data taken from the explosion records provide an independent check and are plotted on the profiles. All depths are based on 4800 ft/sec sound velocity and are about 100 fathoms too shallow as a result.

On the basis of topography alone the area is divided into four areas as shown in Figure 10. Note that Figure 10 is composed as a sort of three-dimensional chart with a latitude scale at the top and approximate longitudes indicated on the depth profiles. For accurate location of the profiles refer to the dashed lines of Figure 9. The northern and central areas are characterized by a relatively smooth bottom (profiles C, D, and the northern part of E), the eastern area by hills or ridges up to 2400 ft high (central portion of E, F, G, and H); the southern area by a gentle upslope to the ridge which forms the northern edge of the Brownson Deep (southern portion of E, F, and G); and a western area whose main topographic feature is a low ridge, seen on the two westernmost profiles on an otherwise flat bottom (A and B). The same division follows from a study of the

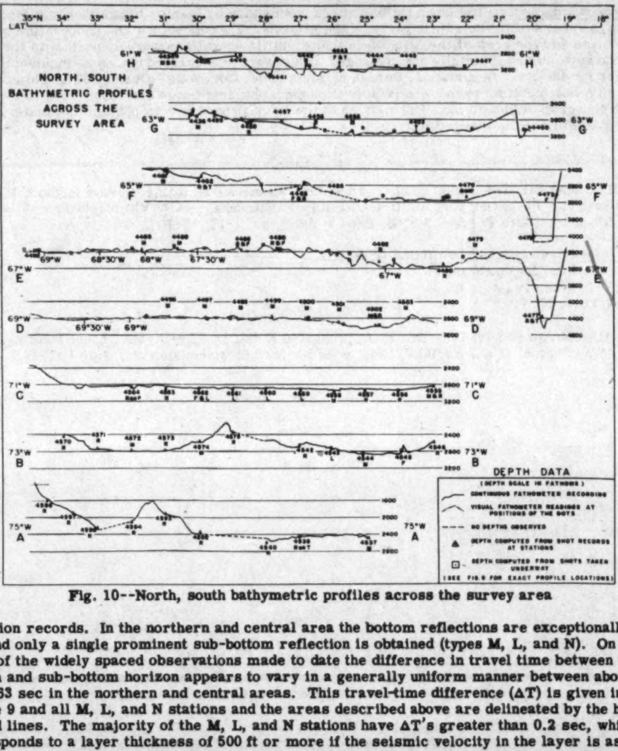

Fig. 10--North, south bathymetric profiles across the survey area

explosion records. In the northern and central area the bottom reflections are exceptionally clear-cut, and only a single prominent sub-bottom reflection is obtained (types M, L, and N). On the basis of the widely spaced observations made to date the difference in travel time between the bottom and sub-bottom horizon appears to vary in a generally uniform manner between about 0.05 and 0.63 sec in the northern and central areas. This travel-time difference (ΔT) is given in Figure 9 and all M, L, and N stations and the areas described above are delineated by the heavy dashed lines. The majority of the M, L, and N stations have ΔT's greater than 0.2 sec, which corresponds to a layer thickness of 500 ft or more if the seismic velocity in the layer is assumed equal to or greater than that in sea water. Records from the eastern area differ markedly from those in the northern and central areas. These also differ in character among themselves but are all relatively complicated (types R, T, and F). In the southern area only a few records of useable quality have been obtained, but these indicate type M records are to be obtained on the gentle slope, while the records in the Brownson Deep are complicated in character, probably types R, F, and T. In the western area various types of records are found with M, N, and L tending to fall on the flat places and R, T, or F on the ridge or the continental slope.

Conclusions--The instrumentation and technique described have obtained records of energy from reflecting horizons below the ocean floor in deep water. A system of classification of deep sea-reflection records is presented with suggested geologic interpretation. The record types correlate in a general way with bottom topography. These conclusions are based on very widely spaced observations over the area considered, and were drawn from techniques which have since been considerably improved upon and are subject to further improvement. The inferences drawn from the data have been made conservatively and are subject to revision and amplification as more and better results are obtained. Hence this report should be considered preliminary. The work is continuing and will furnish more detailed information about this and other areas of the deep oceans.

Acknowledgments--The observations at sea were made by Stanley Bergstrom assisted by various members of the scientific party on the Atlantis. The assistance and cooperation of Captain Adrian Lane and the crew of the Atlantis in the scientific operations were important to the success of the survey and are gratefully acknowledged. (This work was carried out as an incidental part of research for the Navy Department, Bureau of Ships under Contracts NObs-39092 to Columbia University, sub-contract to the Woods Hole Oceanographic Institution and NObs-2083 to the Woods Hole Oceanographic Institution. Permission of the Navy Department to publish this material is hereby gratefully acknowledged.)

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SIMILITUDE OF ARTIFICIAL AND NATURAL FOGS

J. Ross Heverly

Abstract--Experimental studies of condensation nuclei and laboratory fog investigations have largely been based on the assumption of adiabatic conditions. This study includes a check on the validity of this assumption under a number of different conditions. The median size and the number of fog droplets were determined during the formation and evaporation of artificial fogs. The effect of nearness to a water surface is also studied. The results for the artificial fogs are compared with measurements of natural fogs. The jet method, used in sampling artificial fogs, is found to yield out-of-door measurements that are in line with those obtained by the sedimentation method. The experiments show that, due to the non-fulfillment of adiabatic conditions in the laboratory, temperature and moisture conditions in an air sample cannot be calculated from measurements of pressure. They show, too, that condensation processes produced in the laboratory are adequate for studying the type and, to some extent, the size distribution of condensation products as they occur in nature.

Introduction--In most of the laboratory investigations of fog formations that have been made, volume ratios have been measured, and expansion ratios, temperatures, and "supersaturation" ratios have been calculated on the assumption of adiabatic conditions. This has been particularly true with regard to experimental studies of condensation nuclei [JUNGE, 1935]. In the present study [HEVERLY, 1948], fogs have been formed and dissipated under various non-adiabatic but controlled and measured conditions. The results obtained are compared with outdoor measurements of natural fog.

Experimental studies and results--The expansions involved in the formation of the various laboratory fogs in this experimental investigation took place in time intervals ranging from one second to one minute. These expansions indicated the degree to which the assumption of adiabatic processes is valid under some different expansion rates and conditions. In the case of a fog chamber which consisted of a 24-liter Pyrex flask, both with and without a small amount of water, the coolings observed (thermocouple at center of flask) were far from moist adiabatic or dry adiabatic cooling, respectively. The results are summarized in Table 1.

Table 1--Actual cooling of air in a 24-liter Pyrex flask as contrasted with adiabatic cooling

Time for expansion	Pressure reduction	Expansion ratio	Observed cooling		Corresponding adiabatic cooling	
			Dry	Moist	Dry	Moist
sec	mb		°C	°C	°C	°C
27	170	1.21	3.5	2.2	15.4	6.2
63	340	1.54	4.3	2.8	33.0	14.0
4	160	1.19	. .	4.7	. . .	5.8
13	330	1.52	. .	6.6	. . .	13.6

In Table 1 the heat produced by the condensation of water vapor into fog droplets is clearly evident. The observed cooling when water was present in the flask (observed cooling - moist) is seen to be about one-third less than the cooling when no water was present (observed cooling - dry). It may also be noted that when approximately the same expansion ratios were reached in different amounts of time the more rapid expansion came closer to being adiabatic. For example, it is seen that an expansion ratio of 1.2, reached in a time of 27 sec, produced a moist cooling of about one-third of the corresponding adiabatic cooling. In contrast, an expansion ratio of 1.2, reached in a time of four sec, produced a moist cooling of about four-fifths of the corresponding adiabatic cooling.

During the formation of a fog in the Pyrex flask, the median size of droplet and the number of droplets at first increased (see Table 2). This is due to the increasing relative vapor pressure of the water, as compared with the saturation pressure of the expanded air which was at a lower temperature than the water surface. Later in the formation, the median size decreased because a slower cooling rate permitted greater heat transfer to the system. The increase in difference between the observed and the moist, adiabatic cooling rate, with increase in time for expansion, is evident from Table 2. After the formation of a fog, the heat transfer from the surroundings raised the temperature within the flask, causing a rapidly decreasing size and number of droplets. These results are summarized in Table 3.

Table 2--Averaged data on the formation of fog; room temperature, 27°C; 24-liter Pyrex flask; one inch above water surface

Time for expansion	Pressure reduction	Expansion ratio	Observed cooling	Corresponding moist adiabatic cooling	Median size of drops	Estimated relative number of drops
sec	mb		°C	°C	micron	
5	35	1.04	0.6	1.1	5	1
10	70	1.08	1.1	2.3	7	1.5
15	100	1.12	1.5	3.5	8.5	2.5
20	140	1.16	1.8	4.9	8.5	2
25	170	1.21	2.1	6.2	7	2
30	200	1.27	2.4	7.7	6.5	. . .
45	270	1.39	2.8	10.5	6	. . .
85	410	1.72	3.2	17.5	6	. . .

Table 3--Averaged data on the evaporation of fog; room temperature, 27°C; 24-liter Pyrex flask; one inch above water surface

Time after expansion	Pressure reduction	Temperature departure from room temperature	Median size of drops	Estimated relative number of drops
sec	mb	°C	micron	
0	140	1.8	8.5	1
25	140	0.70	4.5	0.5
35	140	0.45	3.5	0.3
50	140	0.30	3.5	0.05
55	140	0.25	2.5	0.05
60	140	0.20	none	. . .

For the measurement of their size, the fog particles were embedded in a vaseline film [HOUGHTON and RADFORD, 1938] by means of a small differential air pressure applied through a small jet placed above the film [KINOSHITA and UCHIYAMA, 1932]. In the case of the 200 mb or greater pressure reduction, the diameter of the fog-droplet pattern became greater than that of the cover glass used. Hence no estimate of relative numbers can be given for these pressure reductions. Figure 1 is a photomicrograph showing a typical fog pattern. The fog droplets in this case range from 1.5 to 15 microns in diameter (each numbered division of the scale in Figure 1 represents 100 microns).

Fog-formation data were also obtained at different expansion rates. The median size drop formed in a laboratory fog was found to depend on the time required to produce the fog only in the case of relatively large (about 1.4) expansion ratios and relatively large time intervals (of the order of tens of seconds). The effect of nearness to a water surface was found to be of greater magnitude. Eight inches above the water surface as compared to one inch, produced a decrease of one-third in the median size, although the number of particles was approximately the same. This is due to the relatively slow diffusion of water vapor into air with consequent large vapor pressure gradient so that less water is available for the fog particles at a greater distance from the water surface. This phenomenon has its equivalent in nature in the formation of shallow steam fogs over relatively warm water surfaces.

In outdoor measurements of natural fogs, the jet method results were found to be in line with results obtained by the sedimentation method in which the fog droplets were permitted to settle onto the film by gravity. As an example, one fog, on August 7, 1947, was found to have the size distribution given in Figure 2. It is apparent that this fog was in the process of evaporation because of the decrease of drop size with time. Also, this particular fog became more homogeneous

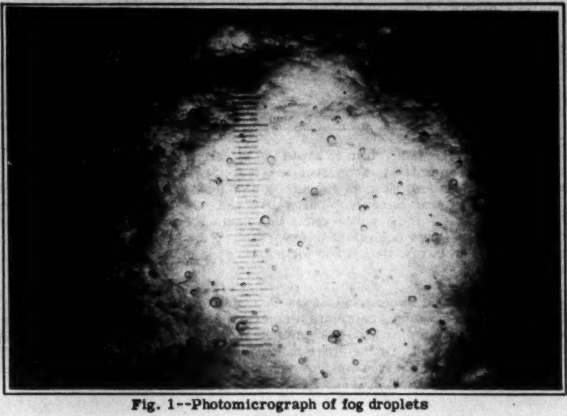

Fig. 1--Photomicrograph of fog droplets

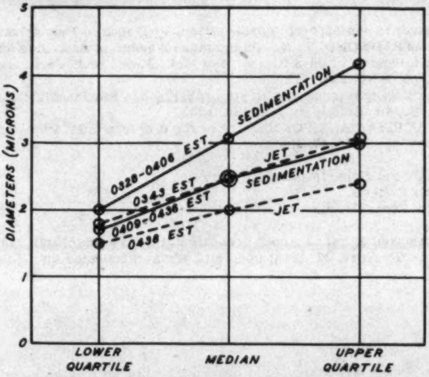

Fig. 2--Size distribution of fog particles in a natural fog on August 7, 1947

during the observation. Nevertheless, the jet method seems to be somewhat more efficient in fog sampling than the sedimentation method because more of the smaller droplets are forced into the vaseline film. In the sedimentation method, air currents may prevent the settling of these smaller droplets.

The mean-diameter distribution for all of the natural fogs observed (the case discussed above involved relatively small size droplets) was quite similar to the mean diameter distribution obtained for the artificial fogs. The results obtained are summarized in Table 4.

It may be noted in this table that the lower quartiles and medians are practically the same but that the upper quartile is somewhat higher in the case of the artificial fogs.

Table 4--Mean-size distribution of all artificial and natural fog-droplet diameters

Type of fog	Lower quartile	Median	Upper quartile
	micron	micron	micron
Artificial	4.5	7.3	11.5
Natural	4.5	7.2	9.1

In this investigation, care was taken to avoid the effects of coalescence. It appears that coalescence in drop measurements has been overlooked or, at least, underestimated by a number of experimenters. In one instance, when an especially high density of the droplet field was obtained, a great deal of coalescence was microscopically observed. Coalescence took place instantly whenever droplets of water in the vaseline came into contact with one another. Unless the droplets are separated by a distance equivalent to several drop diameters, coalescence appears to be a serious factor and is, probably, the reason for some of the high medians of fog-droplet sizes reported in the literature.

Conclusions--The present experiments show that, due to the non-fulfillment of adiabatic conditions in the laboratory, one cannot calculate temperature and moisture conditions in an air sample from measurements of pressure; it is necessary that these quantities, if essential to interpretation of results, be directly observed. On the other hand, condensation processes produced in the laboratory are adequate for studying the type and, to some extent, the size distribution of condensation products as they occur in nature.

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EFFECTS OF WIND SHEAR ON SOME ASPECTS OF CONVECTION

Joanne Starr Malkus

(Contribution No. 457, from the Woods Hole Oceanographic Institution)

Abstract--A jet ascending through a fluid possessing vertical shear of the horizontal wind will show a difference in horizontal velocity from that of the ambient air. The magnitude of the difference is shown to be a function of the vertical shear and the rate of entrainment of mass into the jet.

The effect of this relative horizontal velocity on the slopes of dry thermals and on cumulus cloud processes is discussed. The observed horizontal asymmetries in the turbulence associated with trade cumulus are offered as an example.

Relative velocities between jet and surroundings

Theory--The parcel method of dealing with convection processes envisions a rising bubble of air ascending through an environment at rest. A modification, the so-called slice method [BJERKNES, 1938] takes into account the compensatory sinking of the environment. The importance of mixing between the rising air and its surroundings has required increasing attention, and recently the analogy between the hydrodynamical jet stream with its entrainment of mass from the environment and atmospheric convection has been emphasized [AUSTIN, 1948; BYERS and BRAHAM, 1948; STOMMEL, 1947]. This work has demonstrated the significant amount of mass entrainment which occurs in the rising cumulus or thermal, and entrainment has been evaluated by synoptic methods [STOMMEL, 1947]. The rate of mass entrainment is found to be of the order of one part external air to four parts cloud air every 50 mb.

Up to the present time, meteorologists have discussed a jet rising through an environment at rest. Actually, however, a variation of the horizontal wind with height is almost always observed. The question of the modification of the ascending jet by a vertical shear therefore arises.

Returning for a moment to the earlier parcel method, it is clear that a bubble ascending to a region where the wind differs from that at its origin carries its initial horizontal momentum, and therefore arrives at the upper level with an excess or deficiency of horizontal velocity, depending on the sign of the shear. Thus, if cumulus convection occurred without friction (which gives rise to mixing), it is easily seen that cumulus clouds and thermals must acquire horizontal velocities relative to the air surrounding them. Mixing, or entrainment of mass, on the way up can be seen as a factor reducing this differential velocity. Only if the mixing were infinitely great, however, could the difference be reduced to zero.

A quantitative estimate of the relative horizontal velocity between the ascending jet and its surroundings can be made very easily, under only one simplifying assumption. That assumption is based on the results of theoretical work done by TOLLMIEN [1926] and discussed by GOLDSTEIN [1938, pp. 592-600], ROSSBY [1936], and SCHMIDT [1948]. The theoretical treatment concerned the symmetrical jet which is homogeneous with its environment. For this case it was shown that the flux of mass increases linearly with distance from the nozzle. Linear increase of flux is assumed, therefore, as a beginning approximation for the atmospheric case.

Some function must also be chosen for the relation between ambient wind velocity and elevation. It turns out that this function enters the equations so simply that only a quadrature with respect to height is involved, and therefore any analytic expression which approximates the wind profile is quite satisfactory. For the purpose of simple illustration, a linear wind profile is taken here.

The problem is to find the horizontal velocity of the cloud, u_c (where the x-direction is taken to be that of the horizontal wind velocity at the level in question) as a function of elevation z. In considering a small, vertical segment of the ascending jet (see Fig. 1) between the levels z and z+dz, let M be the upward mass flux across the entire rising column, at z, where the horizontal cloud

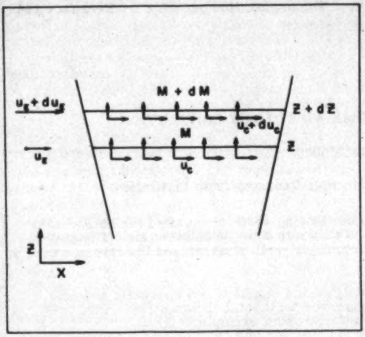

Fig. 1--Schematic vertical section of an ascending jet

velocity is u_c, and the horizontal environment wind velocity is u_E. Let the flux of outside air into the cloud between z and z + dz be dM. Since a steady state is assumed, the flux at z + dz is M + dM. Let the horizontal cloud velocity at z + dz be $u_c + du_c$ and the outside wind velocity be $u_E + du_E$.

Beginning with the law of conservation of momentum, it is clear that the horizontal momentum of the air inside the jet at the level z + dz must equal the sum of the momenta of its component masses at level z, or that

$$(M + dM)(u_c + du_c) = Mu_c + u_E dM \;.\;.\;.\; (1)$$

The exchange of momentum between jet and environment is accounted for by the term $u_E dM$ [see GOLDSTEIN, 1938; SCHMIDT, 1948; TOLLMIEN, 1926]. Multiplying out, neglecting products of differentials, and dividing through by dz, we obtain

$$u_c\, dM/dz + M\, du_c/dz = u_E\, dM/dz \;.\;.\;.\;.\; (2)$$

After substitution, according to the earlier assumptions, namely that

$$M = M_0 + kz \;.\; (3)$$

and

$$u_E = u_{0E} + hz \;.\; (4)$$

where the subscript 0 refers to quantities at the jet base, k is the rate of increase of mass flux with height, and h is the rate of increase of the x-component of the wind with height, and after rearrangement, the following first-order differential equation is obtained.

$$du_c/dz + u_c k/(M_0 + kz) = (ku_{0E} + khz)/(M_0 + kz) \;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\; (5)$$

The solution is found to be

$$u_c = c/(M_0 + kz) + (2ku_{0E}z + khz^2)/2(M_0 + kz) \;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\; (6)$$

where c is the arbitrary constant of integration. If at the lower boundary of the jet (where z = 0), $u_c = u_{0E}$, then

$$c = M_0 u_{0E} \;.\; (7)$$

and the solution can be rewritten in convenient form as

$$u_c = u_{0E} + Khz^2/2\,(1 + Kz) \;.\; (8)$$

where $K = k/M_0$.

Equation (8) shows that the relative horizontal velocity between cumulus cloud (or thermal) and its environment is a function of both the external wind shear and the rate of mass entrainment. A quantitative example has been plotted in Figure 2.

In this graph, the vertical shear of external wind represented by the solid curve is three m/sec in 1200 m. Since shear enters the relative velocity linearly, a simple vertical scale adjustment will give any desired linear shear. The dotted curve gives $u_c - u_{0E}$ as a function of z for a rate of entrainment such that the ascending mass flux at the top of the 1200 m layer is 2.5 times that at the bottom. This rate is slightly higher than the average rate found by STOMMEL [1947] in trade cumulus, and higher than the larger value used by AUSTIN [1948] for middle-latitude convective clouds. The dashed curve represents $u_c - u_{0E}$ when the rate of entrainment is doubled.

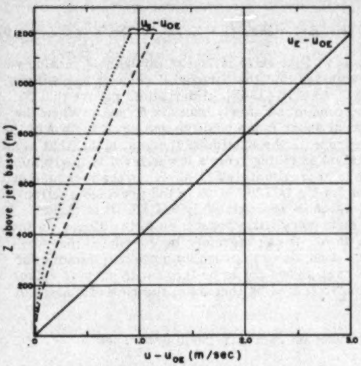

Fig. 2--Graph showing cloud velocity u_c as a function of height, compared to external wind velocity u_E; dotted curve is for rate of entrainment such that mass flux at top of cloud is 2.5 times that at base; dashed curve is for double this rate of entrainment

The relative horizontal velocity between jet and surroundings, after a 1200-m ascent, is on the order of two m/sec. Doubling the rate of mass entrainment makes a difference of only 0.3 m/sec. It is easily seen that doubling the external shear, on the other hand, doubles the relative velocity; hence shear is the more critical parameter.

Evidence--Cumulus clouds have frequently been noted to be moving with a speed different from that of their environment, but conclusive quantitative data are so far lacking. However, one case of interest was revealed by a series of lapse-time motion pictures taken at Woods Hole Oceanographic Institution on February 21, 1948. Many observers noted that the convective cumulus clouds over the water apparently were moving in the downwind direction with a speed faster than the wind, since cloud fragments were seen streaming out upwind. A subsequent examination of upper winds revealed, indeed, a strongly negative wind shear throughout the region below the estimated cloud base.

Slopes of thermals

It is but a simple step from (8) to the calculation of the actual slope of the ascending thermal chimney. To give an approximate picture of how this slope is modified by vertical wind shear and mass entrainment, a constant rate of ascent of the air $\bar{v}$ is assumed.

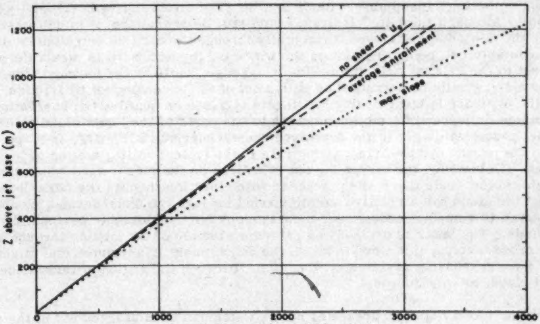

Fig. 3--Graph showing actual slope of thermal when horizontal base velocity u_{0E} is 2 1/2 times the rate of ascent

Then, under steady-state conditions, the horizontal displacement x of the thermal at level z is

$$x = \int u_c \, dz/v + \text{constant} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

where z/x is the slope of the thermal, and where the constant of integration can be evaluated from the boundary condition that at the base of the thermal, its x-displacement is zero.

Substituting u_c from (8), the solution is

$$x = u_{0E}\, z/v + h/2K^2v\, [(1 + kz)^2/2 - 2\,(1 + Kz) + \log_e (1 + Kz)] + 0.75h/K^2v \quad \ldots\ldots (10)$$

In Figure 3, the solid line represents a thermal without external shear (or without mixing with an environment with shear), when the scale is so adjusted that the horizontal velocity u_{0E} stands in a ratio of 5/2 to the rate of ascent. (According to LANGE [1945], glider pilots report that 85 per cent of thermals observed at 1000 ft altitude ascend more slowly than six ft/sec.) When the vertical distance is taken as 1200 m, and the external shear made positive and equal to that of the previous example (see Fig. 2), the dotted curve represents the maximum thermal slant (that slant corresponding to entrainment so high that the cloud mass rising from a lower level is negligible compared to that entrained). The maximum slope is approximately 5/1.5. When the increase of mass flux is reduced to a reasonable value, that of 2.5 M_0 in 1200 m as in the previous section, the slant is shown by the dashed line, the slope of which is approximately 5/1.86. It is clear from the graph that doubling the entrainment will make very little difference in the slope. In fact, at 1200 m it increases the x-distance by less than 75 m. It can therefore be concluded that for most thermals, a slope calculated from the surface wind alone is probably quite satisfactory for soaring purposes. The effects of wind shear have been shown not to be large with normal values of mass entrainment, and furthermore, on days characterized by thermals, the rate of change of wind with elevation is usually relatively slow.

Effects of the relative horizontal velocities on cumulus-cloud processes

Discussion--Horizontal translation of ascending jets of air relative to their surroundings may be expected to influence the growth and motion of cumulus clouds.

Visual observations of such clouds reveal, especially when the processes are accelerated by lapse-time motion pictures, that a cumulus is not simply an aggregate of droplets moving as a coherent body, but rather that it is a transient, dynamic balance between rapid growth and equally rapid destruction. For example, it is a common observation that when an average midsummer cumulus moves out over the cooler ocean, thus leaving its energy source, the entire cloud disappears in five to 20 min time. Lapse-time photographs further suggest that part, at least, of a cloud's motion is achieved by growth in some sections and dissipation in others.

The connection between these observations and the predicted relative horizontal jet velocity can now be made. Although a detailed analysis would still be premature, it is quite reasonable to suppose that as the ascending jet moves horizontally through the air, the entrainment of outside air becomes asymmetrical, being greatest on the windward (by windward is meant the upwind side with respect to the relative velocity $u_r = u_E - u_c$) edge, while on the leeward side, parts of the liquid cloud may actually be detrained or pulled out of the ascending jet by friction. At the present time, the evidence in favor of this hypothesis is based on qualitative observations only: First, it is common on lapse-time motion pictures to see parts of the liquid cloud streaming out on just one side, becoming caught in the downward countercurrent [SCHMIDT, 1948, pp. 13-18] just exterior to the jet and disappearing, giving rise to the typical rolling motion associated with moving cumulus. (Commonly, the streaming out is noticed on the side toward which the cloud leans with height, since winds more often increase with elevation through the cloud layer. This would imply that the cloud has a relative motion upwind through the air.) Second, clouds have often been observed to remain standing near mountaintops for considerable periods, despite fairly strong winds. The latter is probably an extreme example of air moving through a cloud. The horizontal cross-section of a cloud in which the entrainment is asymmetrical might be expected to show a corresponding asymmetry, therefore, between the region of turbulence and the observed liquid cloud, as in Figure 4.

In Figure 4, the cloud region represented by δ, which has been dragged out of the ascending jet, can be expected to be dying out, while a new cloud section is forming in region D. Thus the cloud as a whole might be said to have a component of propagation velocity due to new growth on one edge and decay on the opposite edge. Whether this component adds to or subtracts from the external wind velocity has been shown to be critically dependent upon the shear. That the turbulent region can be associated with the rising jet and a nascent or vigorous cloud is corroborated by much evidence [AUSTIN, 1948; BYERS and BRAHAM, 1948] that young, growing cumulus clouds are highly turbulent, while old or dissipating clouds are not. However, the test of this, as of any other hypothesis must lie in experimental verification, or observational examples. Such an example appears to be offered by a series of horizontal traverses through trade cumuli made by the Wyman-Woodcock expedition of April 1946 [WYMAN and COLLABORATORS, 1946].

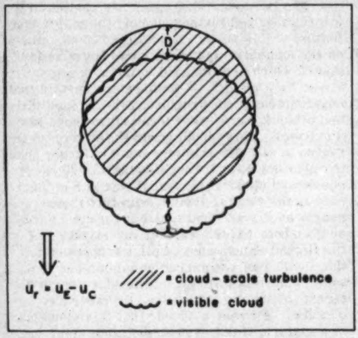

Fig. 4--Schematic illustration of expected asymmetry between liquid cloud and turbulence of ascending jet, where u_r is relative horizontal velocity in the positive x-direction between jet and ambient air; D is the region of turbulence and no cloud, while δ is the region of cloud and little or no turbulence

The observations--Trade cumulus commonly are found in patches, roughly 100,000 ft in diameter, separated by wider clear areas. Their bases are at the top of the well-mixed and almost dry-adiabatic homogeneous layer which extends ordinarily to about 2000 ft above the sea. The cloud tops usually terminate at the base of the stable layer remaining from the trade inversion, which occurs on the average at 7500 to 8000 ft, with only an occasional break-through. Part of the routine of the 1946 Caribbean expedition were airplane traverses made by a Navy patrol plane (PBY-5A) which maintained an airspeed of about 100 knots, during which an angle of attack meter and an accelerometer were recording continuously. The results of those flights in the wide areas entirely free from clouds have been discussed by LANGWELL [1948], who showed that the sum of the vertical speeds (called here vertical gust speeds) obtained by the two instruments together can be regarded as a relative measure of the small-scale turbulence present. Fortunately, several traverses were also made through regions containing scattered or broken cumuliform clouds, at altitudes ranging from 3000 to 7000 ft, but most commonly at 6000 to 6500 ft. When these data were worked up following the method described by Langwell, it was found in general that the vertical gust speeds outside the clouds averaged 0.2 m/sec while those inside the clouds averaged slightly higher than 1.7 m/sec. Exceptional regions, however, at the cloud borders occurred with regularity. With only one exception (discussed later) there was a region 600 to 1000 ft in extent just outside the visible cloud where gust speeds as great as or often greater than those inside the cloud were detected. Furthermore, corresponding regions were noted just inside the opposite border of the cloud where speeds nearly as low as the outside average were measured. These recordings of cloud-scale turbulence in the clear, and clear-scale turbulence in the cloud suggest an asymmetrical picture of trade cumulus like that shown in Figure 4. However, before these regions can be identified with the D and δ, respectively, of Figure 4, it must be shown that they do not arise from instrumental or personal error, and that they bear the predicted relation to the vertical shear of horizontal wind. That the asymmetry is real and not due to errors, can be easily demonstrated, and will be shown in the final paragraphs.

The relation between turbulence distribution and the wind structure will be discussed next. There were 11 separate clouds through which traverses were made. Days were chosen for the observations when the easterly trade regime was nearly uninterrupted [WYMAN and COLLABORATORS, 1946], and the wind showed rather little change in direction or speed with height throughout the cloud layer. In ten of the traverses, the plane was flown on a course within a few degrees of the upwind direction. In the eleventh, the plane was flown nearly at right angles to the wind, and hence even the sign of the vertical shear of the wind-component parallel to the plane course would be very difficult to determine accurately. Hence this case is omitted from the discussion. In nine of the ten remaining cases, the shear with height of the headwind component was clearly positive and differed little from one m/sec per 1000 m. In fact, eight of these nine cases were so similar (except in respect to cloud diameters, for which a mean was taken from maps made from the expedition's cloud photographs) that their measurements have been averaged, and the average presented in Figure 5. In these eight cases, the ascending chimney, according to previous reasoning, should have an upwind component of motion, or in other words, the cloud should be drifting downwind with a speed less than the ambient windspeed. The nature of the observed asymmetry in turbulence is in agreement with this supposition. The relative horizontal velocity between jet and environment, computed with the average rate of mass entrainment for trade cumuli found by STOMMEL [1947] averages only 0.2 m/sec at the height of the traverse. Using the average observed δ of 1000 ft, this means that the cloud fragments require 25 min to dissipate after being pulled out from the ascending chimney. In view of the relatively high humidities in the environment (in accordance with BUNKER and STOMMEL [1947] about 70 per cent), this time appears very reasonable.

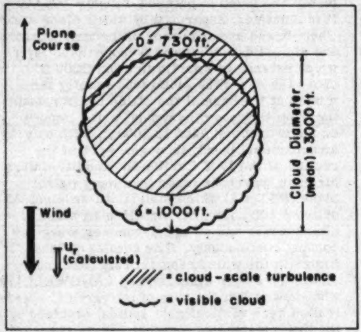

Fig. 5--Average of eight observations of trade cumuli with positive external wind shear (not to scale); note agreement with Figure 4

The two remaining cases are particularly interesting, and further support the major contention of this paper. One of the two was made on the same day and in the same flight as four others which are included in the average shown by Figure 5. It is therefore certain that environment wind structure, relative humidities, and other factors, were identical to those just discussed. This cloud, however, showed no D region at all. Its diameter was far larger than the average flown through, being 15,900 ft. It possessed cloud-scale turbulence (2.3 m/sec) only in the central 7500 ft, with turbulence nearly as low as clear-scale (average 0.67 m/sec) on both edges. Further investigation of the flight records showed pilot reports that this cloud was a towering cumulonimbus from which rain was falling, and therefore much different in structure from the normal trade cumulus. Further evidence that this cloud was in a mature, if not even dissipating, stage came from a computation by the method of STOMMEL [1947] of its rate of mass entrainment. A sounding taken inside this cloud showed, for five successive ten-millibar intervals a negative rate of mass entrainment. Since clearly negative mixing is quite impossible, it is likely that this cumulonimbus was beginning to evaporate in parts. Thus a higher specific humidity could be found in it at successive heights than can be accounted for by any positive mixing between the cloud and its surroundings.

The final case showed a very slight negative shear in the headwind component. The headwind was 13 mph at 1000 ft and 12.2 mph just above the plane at 6700 ft. The asymmetry should therefore, according to theory, be very slight, and reversed in sense from that pictured in Figure 5. Figure 6 shows that this indeed was the case. Greater turbulence than that inside the cloud is found in this case on both outside edges. This bears out a prediction by SCHMIDT [1948] that the ascending jet may often be broader in extent than the visible cloud, the liquid droplets growing in the chimney center. In this case the turbulent region in the clear is broadest, however, on the upwind side in agreement with a calculated, small relative velocity of the cloud downwind.

Possible instrumental or personal errors--From the data presented in the last section, it is already clear that the observed asymmetries in turbulence cannot be due to instrumental errors or lags. This is apparent for three reasons. First, the turbulence is often greater outside than inside the cloud. Second, the asymmetry is not always such that the turbulence (region D) is found only upon the exit of the plane from the cloud (see Fig. 6 for an example). Third, the asymmetry does not occur in every cloud traversed, but seems to be a feature associated with common trade cumulus and was not found in a mature cumulonimbus.

That the results cannot be due to delay in the observer's reaction time, resulting in a late recording of entrance into and exit from the visible cloud is also plain. In general, the cloud was recorded by the observer before turbulence was detected by the instruments and its end marked before the instruments stopped recording cloud-scale turbulence.

As final evidence, a record from the flight accelerometer [VINE, 1945] is reproduced in Figure 7. Since the instrument was very nearly critically damped, two or three complete oscillations of the pen after the turbulence has ceased is completely impossible. Furthermore, the time required after an accelerative pulse for the amplitude to reduce from peak to 1/10 peak value is 0.4 sec. The time during which turbulence of cloud amplitude or greater was observed in the clear outside the cloud edge was six to eight sec. It must therefore be concluded that the asymmetries discussed are real. (Further analysis of each other phase of the instrumentation substantiates the conclusions drawn, but for brevity's sake will not be discussed.)

Acknowledgments--The writer would like to thank Patricia A. Langwell for the use of her analyzed records, data, and files, and for innumerable valuable suggestions and discussions. Thanks are also due to Bernhard Haurwitz for helpful criticisms, and to Andrew F. Bunker,

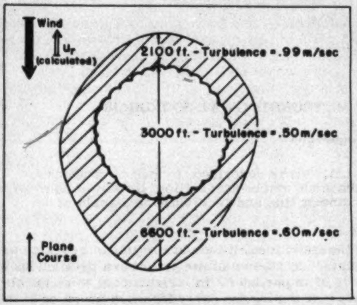
Wind
U_r (calculated)
2100 ft. - Turbulence = .99 m/sec
3000 ft. - Turbulence = .50 m/sec
6600 ft. - Turbulence = .60 m/sec
Plane Course

Fig. 6--Single case illustrating trade cumulus accompanied by slight negative external wind shear (not to scale); note reversal of asymmetry as compared with Figure 5; the average value of turbulence measured on this traverse away from the cloud was 0.22 m/sec

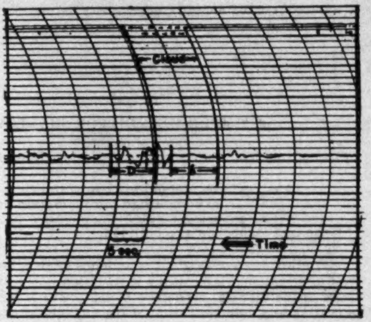

Fig. 7--Actual accelerometer record for one of the cases presented schematically by Figure 5; note time elapsed during passage through regions δ and D; the aircraft was flown at 100 knots airspeed.

Henry Stommel, and Alfred H. Woodcock who participated in many phases of this work. Observational phases of the work have also been discussed with H. R. Byers, Harry Moses, and Chester Newton of the Army-Navy-Weather Bureau Thunderstorm Project. The field work of this project was carried out under contract with the Bureau of Ships of the United States Navy Department and study of the results is being continued under contract with the Office of Naval Research.

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A SIMPLE METHOD FOR SHALLOW METEOROLOGICAL SOUNDINGS

Hans Neuberger

Abstract--A method for use with captive balloons is described, by means of which the signals from a modified chronometric radiosonde can be transmitted through a non-conducting mooring string. The devices for transmitting and receiving the signals of the meteorosonde are outlined.

Shallow meteorological soundings up to a few thousand feet altitude are useful in research as well as in student laboratory instruction. For example, in studies of air pollution a detailed knowledge of the thermal structure of the lower layers is of importance. In instructional work the observation and demonstration of the changes in lapse rate during the early forenoon hours or of the diurnal variation in temperature and humidity at various altitudes are of interest. Employment of the ordinary radiosonde for these and similar purposes proves rather expensive, especially when meteorological information from aloft must be collected at short intervals over a longer period of time. Moreover, a detailed picture of the structure of the lower air layers cannot generally be obtained with a free radiosonde because of its too rapid ascent. On the other hand, the horizontal drift of slowly ascending free balloons often does not permit the study of specifically local conditions. The use of captive balloons is advantageous for shallow soundings, particularly since the advent of the "Kytoon" (which flies on the principle of both kite and balloon) has made the wind an asset in the technique of captive balloon ascents.

For a given lifting force of the balloon, the height to which captive soundings can be made, depends on the weight of the instruments to be carried aloft and on the weight of the mooring line. With regard to the weight of instruments, the direct-recording type such as, for example, the Dines balloon meteorograph [MIDDLETON, 1941, p. 188] can perhaps be constructed lighter than any other type. However, the records are not immediately available and a possible failure of the instrument to record properly will not be detected until the balloon has been landed. The radiosonde is ordinarily too heavy for captive ascents because of the battery requirements for the radio-signal circuit. The direct transmission of electrical signals through the mooring line necessitates the use of a cable with two conduits. While the weight of such a cable is no serious consideration for ascents of a few hundred feet altitude, for higher ascents a definite weight saving is achieved by the method described below. In other words, a balloon of a given lifting force has a higher ceiling using this method than with wire cable. Another, though minor, aspect of the use of an electrically conducting mooring line is the need for a reel with sliding contacts for the lead-in connections.

Light weight may be combined with immediate availability of the signals from the meteorosonde by the use of elastic waves as signal carriers traveling through a mooring line consisting of linen thread, nylon, or any other suitable string. The method employs a chronometric radiosonde [MIDDLETON, 1941, p. 192] which has been stripped of all its radio parts and the unessential portions of the frame and housing. Also the barometric element may be removed as the altitude can be determined from the length of the paid out string and the elevation angle of the balloon. This instrument skeleton to which a set of two or more pencil batteries has been attached, is sheathed in a thin, more or less streamlined plastic or shellac-coated paper casing with a vane to direct the temperature and humidity elements into the wind for ventilation (see Fig. 1).

Electrical contacts in the instrument are closed at time intervals which by calibration furnish temperature and humidity data. In the circuit there is also a buzzer fastened to the mooring string. The effectiveness of the buzzer in setting up vibrations in the string depends on the direction of the oscillations relative to the string as well as on the frequency of oscillation. The vibrator must be constructed so that strong longitudinal elastic waves are set up in the mooring string. Because the transmission of these waves is better with greater tension on the string, it is essential that no more string be paid out when the balloon has reached its ceiling. There is no noticeable interference with the sound transmission when auxiliary balloons are fastened along the mooring line for additional lift. Experiments with nylon cord showed that the transmission of sound remains good even when the cord is slack, whereas in a slack linen string the transmission deteriorates rapidly with additional length of string.

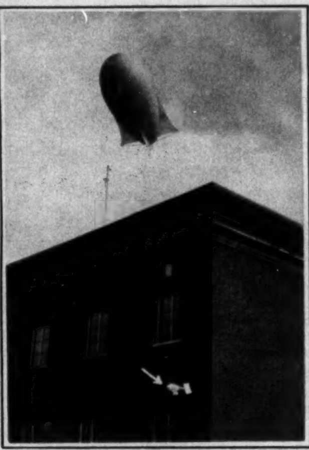

Fig. 1--Kytoon with modified chronometric radiosonde

As regards the frequency of oscillations, it was found that 50 to 120 cycles per sec were most suitable. In this range of frequency, not only was attenuation of sound in the string at a minimum but also the contrast with the high pitched whining noise occasionally made by the wind was greatest. Figure 2 shows a schematic diagram of a buzzer which has produced audible signals through a string more than 5000 ft in length. The weight of such a buzzer is about 100 gm. There are several other possibilities for buzzer construction; for instance, the soft-iron plate P in Figure 2 can be replaced by another stationary electromagnet with unlike poles opposing those of the movable magnet. In this way the intensity of vibrations is increased, but so is the weight. Solenoids with vibrating plungers may also be employed.

The sound signals thus transmitted through the string can be received at the ground aurally with the aid of a mechanical phonograph reproducer fastened to the string as shown in Figure 3, and connected to stethoscope ear pieces by rubber tubing. Upon hearing the signal the operator presses a button to mark the time on the tape of a chronographic recorder. For aural reception it is necessary to slow down the rotational speed in the helical contact of the meteorograph in order to reduce the effect of the error caused by the personal reaction time of the observer.

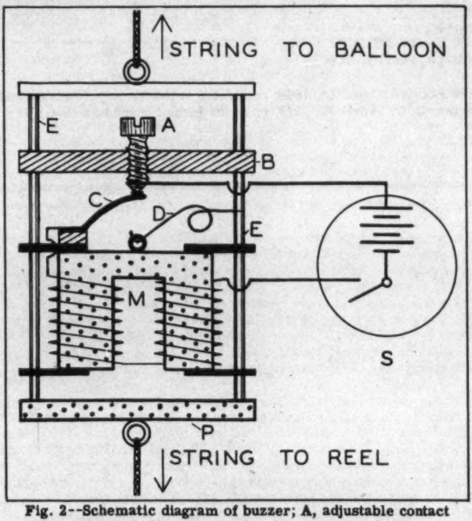

Fig. 2--Schematic diagram of buzzer; A, adjustable contact bolt set in bakelite plate B; C, contact spring; D, wire spring lifting electromagnet M guided by brass rods E; P, soft-iron plate; S, meteorosonde switch with batteries

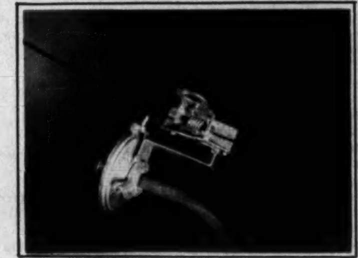

Fig. 3--Mechanical phonograph reproducer for aural signal reception

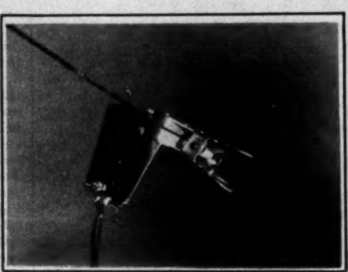

Fig. 4--Phonograph crystal pickup for automatic recording of signals

For automatic recording a phonograph crystal pickup has proven the most suitable receiver (see Fig. 4). The crystal pickup output after electronic amplification activates a relay which in turn operates the marker of the tape recorder. A selective amplifier [PAWLEY, 1933], which responds only to the narrow band of buzzer frequencies, is necessary for the elimination of extraneous noises such as are caused by wind.

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CONVECTIONAL VORTEX RINGS - HAIL[a]

Robert E. Horton

(Posthumous publication, arranged by Richard Van Vliet)

Abstract--Vortex-ring clouds and cloud systems sometimes occur, especially in early stages of violent convective storms. The vortex rings are usually enveloped in cloud in later stages of the storm and are either invisible or not distinguishable from convolutions of cloud. Conditions favorable for the formation of vortex-ring cloud systems are also favorable for severe hailstorms.

It is difficult to account for the uniformity of size and layering of hailstones in many storms on the basis of suspension by varying gustiness in a continually ascending air current. Also it is difficult to account for an ascent velocity sufficient to sustain large hailstones and lasting long enough to permit their formation.

These and other characteristics of hailstones are met if, in some hailstorms, ring-vortex ascent of moist air occurs and hailstones are formed within the vortex ring or rings. This provides requisite ascent velocity for suspension of large hailstones and a much longer period of suspension than direct ascent in the core of the vortex.

It is concluded that hailstorms are of two kinds: (1) Those occurring in conjunction with continuous convective upflow of a column of air without formation of vortex rings, which may be designated as "tubular convective" storms; and (2) those occurring in conjunction with ring-vortex storms and producing much more uniform hail and permitting larger hail to form.

The treatment of the subject is hydrodynamic rather than thermodynamic and details are given of the rheologic or flow conditions involved.

Part 1--Vortex rings in cumulus clouds

Examples--Vortex motion in the atmosphere occurs in well developed cyclonic circulation and with increasing intensity in tropical hurricanes, typhoons, tornadoes, and waterspouts; also, on a smaller scale, in dust whirls. In all these cases the vortex motion is about a vertical axis, one terminal of the vortex filament being at the ground surface. Little consideration seems to have been given to another type of vortex motion, where the filament is closed, forming a vortex ring.

The ordinary, vertically convective system comprising most thunderstorms may be considered hydrodynamically as a rheologic or flow system, resembling the flow through a vertical pipe connecting two reservoirs, with lower pressure in the upper reservoir. This may be called the tubular type of vertical convection.

There is another type of vertically convective system in which a different hydrodynamic system occurs, resembling that where a series of vortex rings is projected vertically upward.

The first published illustration of a storm of this type the author has found, is that shown on Figure 1, reproduced from a drawing by **MEARS** [1931]. This storm occurred in Westmorland, England, in the Pennine Range, about 16^{h}00^{m}, August 28, 1930. Mears described what he saw as follows: "...A huge column of cloud, steadily increasing in height, perhaps half a mile or more in diameter and capped by an immense mushroon top... The column below was not smooth or spiral as in pictures of tornadoes and waterspouts; it was composed of vast 'vortex rings,' which increased in number as the whole edifice grew, until there were at least five. We estimated the height of these rings at about 500 ft each, they were closely touching and rotating visibly at a high speed. The rotation was outwards from the top and downwards, and we thought that the surface velocity might certainly be not less than 60 mph."

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[a] The completion, preparation, and publication of this paper (No. 3 of a series) were made possible by the funds available under a special bequest of the late Robert E. Horton --Ed.

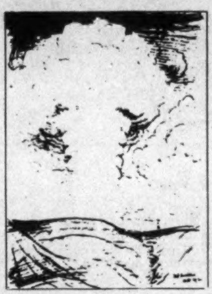


Fig. 1--Sketch of vortex rings observed by Mears

Mears described the formation of this cloud as a result of a warm moist air layer which developed on a flat platform forming the Crossfell sector of the Pennine plateau. The platform is about two sq mi in area, at elevation 2500 ft, and was covered with heather. There was no rain at the location of the observer but heavy thunderstorms occurred nearby that afternoon and evening. Apparently Mears observed a violent vertically convective storm early in its formation. Mears estimated the height of the cloud at about 10,000 ft and the diameter of the torus ring sections as about 500 ft.

Another example of vortex ring cloud is described by CRICHTON [1928]. This cloud was observed over London at $15^{h}30^{m}$ GMT, September 18, 1928 (see Fig. 2). Crichton states that the sky was about 30 per cent covered with cloud, which was neither true strato-cumulus nor cumulus. Crichton states: "The main clouds were not really isolated in the sense that each was entirely independent of the other; they appeared to be intimately connected as their pattern and texture were very similar and although I observed only one complete vortex, other clouds showed signs of having recently been of a vertical type."

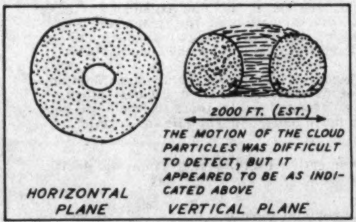

2000 FT. (EST.)
THE MOTION OF THE CLOUD PARTICLES WAS DIFFICULT TO DETECT, BUT IT APPEARED TO BE AS INDICATED ABOVE
HORIZONTAL PLANE
VERTICAL PLANE

Fig. 2--Vortex-ring cloud after J. Crichton, Met. Mag., October 1928, p. 212

Additional examples of vortex ring clouds are given by SHIPLEY [1941], who also gives a sketch of his conception of the cross-section of a thunderstorm. This comprises a small convection tube surrounded by a series of thick horizontal vortex rings or a tubular sheet vortex. He also gives qualitative evidence that somewhat similar conditions result in the production of hailstones and lightning. His model differs in several important respects from either the author's model of a hailstorm (subsequently described) or that of a thunderstorm. Shipley suggests that initially there is a small vortex ring between each pair of larger rings but rotating in the opposite direction and which is broken up at an early stage. The two rings constitute a vortex pair. A vortex pair is often observed behind a moving solid in water. It may, however, be considered as a truncated vortex ring. A single vortex ring is stable and there is no reason for Shipley's assumption.

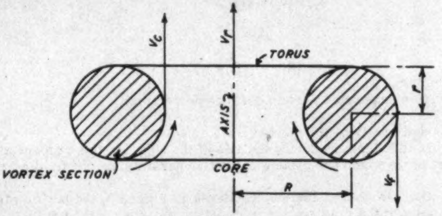
After reading these accounts the author began to watch for the same phenomenon and on one occasion observed, in the mid-afternoon, an example of a succession of vortex rings forming a cumulus cloud and quite as perfect as that described by Mears. The rings appeared to be thicker, relative to their diameter, perhaps 2000 ft. The cloud probably extended to 20,000 ft and there were at least five or six rings wholly unobscured by cloud. There was an evident outward and downward motion of the visible surface of the rings as described by Mears. The cloud system moved rapidly eastward and the rings apparently became enveloped in cloud and there was abundant lightning visible, so that rain was apparently forming. The author was much too fascinated by the magnificent spectacle of this hydrodynamic system, projected, as it was initially, against blue sky, to think of making a sketch. On a few other occasions, in conjunction with active thunderstorms, the author has observed portions of what were obviously vortex rings protruding from one side of a mass of cumulus cloud accompanying a thunderstorm. It is conceivable that this phenomenon may be of quite frequent occurrence but has passed unnoticed. In one instance parts of several vortex rings were visible but apparently not forming a uniform chain with a common vertical axis but appearing more like one side of a small pile of doughnuts.

Characteristics of vortex rings--It seems probable that this phenomenon occurs in conjunction with the initiation of vertically convective storms of a certain type, where, as described by SHOWALTER [1944] "Pronounced rain activity is generally associated with air masses possessing a marked degree of convective instability, which in turn is generally associated with a lower layer of initially high moisture content separated from a much drier layer above by a stable layer or temperature inversion."

If an aperture is broken through the stable-cover layer described by Showalter, the conditions will be those required for generation of a vortex ring or rings as a result of the underlying air gushing up through the opening.

Whether tubular convection or a vortex-ring system develops will depend on the combination of conditions. If the uprush of moist air is gradual and steady, tubular convection only will result. If the uprush is abrupt, strong, and discontinuous, vortex rings will form above the stable layer. As many will form as there are successive impulses.

These statements are easily verified by any one, using the smoke-box apparatus devised by P. G. Tait [DALHEAR, 1894; and RISTEEN, 1898]. The inside of the smoke-box is sprinkled with ammonia and a saucer containing a little hydrochloric acid is set in the box. The top cover of the box must be flexible, as, for example, cardboard. Each successive tap on the cover will eject a quantum of white ammonium chloride smoke, which on ejection will form a perfect vortex ring. What is generated is really a vortex-ring system but in the smoke-box experiment the only visible component of the system is the torus or ring.



VORTEX RADIUS = r
TORUS " = R
CORE " = $R-r$
OUTER " = $R+r$
CORE VELOCITY = V_C
FIELD " = V_f
RING " = V_r
AREA VORTEX SECTION = a

VELOCITY RELATIONS, RING-VORTEX SYSTEM

POSITION	DISTANCE r'	TRANSITIONAL VELOCITY V'	ANGULAR VELOCITY ω'
WITHIN VORTEX SECTION	$r' < r$	$\omega r'$	ω
SURFACE " "	$r = r$	$\omega r = V_c$	ω
FIELD CIRCULATION	$r' > r$	$V_c \, r/r'$	$\omega r^2/r'$

STRENGTH OF VORTEX = CIRCULATION = $2\pi\omega r^2 = 2a\omega$
TORUS VOLUME = $V = 2\pi^2 R r^2$
MASS = $M = \rho V/g$
RADIUS OF GYRATION, VORTEX SECTION = $K = \frac{1}{2}\sqrt{2}\, r = 0.707\, r$
ANGULAR MOMENTUM = MKr

Fig. 3--Ring-vortex system

Referring to Figure 3, a vortex-ring system comprises (1) the torus or ring, (2) the core, which travels upward through the ring, and (3) the surrounding field. The ring travels upward as if its section were being rolled forward by the core. The relative motions of the ring, field, and core can easily be illustrated by laying a pencil across the palm of the left hand, held horizontally.

Then if the palm of the right hand slides forward over the pencil with a velocity v_c, corresponding to the velocity of the core of the vortex ring, the velocity v_r of the pencil, which corresponds to the translational velocity of the ring, will be $v_c/2$ if the left hand is held stationary. If the left hand is moved backward with a smaller velocity v_f, corresponding to the field velocity of the vortex-ring system, then the pencil or torus will travel in the same direction as the core, with a velocity $v_r = (v_c - v_f)/2$. In general, the ring will travel upward with a velocity which may range in value between zero and $v_c/2$, this velocity depending, among other things, on the ratio of the radius R of the ring or torus to the radius r of the ring section. The outer ring radius $R + r$ is greater than the core radius $R - r$, and the volume of the return or field current must, for steady conditions, equal the volume of the upward current in the core. The downward speed of the outer part of the ring will bear more or less the same ratio to the upward velocity v_c at the surface of the core as the reciprocals of the ring and core radii, or

$$v_r = v_c [1 - (R - r)/(R + r)]/2$$

Using this assumption in conjunction with the equation

$$v_r = (v_c - v_f)/2$$

gives

$$v_f = v_c (R - r)/(R + r) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Such a vortex-ring system possesses certain definite properties:

(1) The torus is composed wholly of the ejected fluid.

(2) The torus retains its individuality during the life of the ring. In this respect a vortex ring differs from a traveling wave, in which the system of motion persists but the fluid comprising the wave continually changes.

(3) Within the ring section, or shaded section, as shown on Figure 3, the law of vortex motion prevails. The angular velocity of the ring section is constant, as in a rotating solid.

(4) The ring system is subject to relatively little frictional resistance, behaves like a single mass, and, as may be observed in case of a ring from a smoke-box, it can travel a distance many times its outer diameter on its initial energy before it is broken up by viscous resistance.

If a vortex-ring system is produced by an uprush of air through a cover layer it will possess some properties different from those of an ordinary vortex ring, that is, the torus is composed of moist air and travels into drier air. The ejection of the ring mass through the aperture in the cover layer and the formation of the ring sets some of this drier air in motion as field circulation, forming the core and return current. This air may be carried above its condensation level, becoming cloud, and then travel around the outside of the torus as part of the surrounding field. In this way the torus proper is enveloped in cloud and wholly or partially obscured from view. What is seen is a cumulus cloud.

If a ring vortex of constant density expands or contracts, the relations of the torus radius R and the vortex radius r must be such as to provide (1) constancy of volume and (2) conservation of angular momentum. These results will follow if r varies as $1/R$, and conversely. If a ring vortex expands during ascent, or contracts during descent, as the result of changes of pressure and temperature, the volume of the vortex ring is changed in proportion to the expansion ratio, while the angular momentum remains constant. These conditions are met if the vortex radius r remains constant while the torus radius R varies in proportion to the expansion ratio.

The expansion of vortex rings in ascent is well illustrated by Mear's sketch (see Fig. 1). If there are several successive impulses, producing a chain of vortex rings, as in Mears' sketch, the diameter of the opening of the cover layer may increase with each successive ejection of a ring. Under these conditions the rings later formed will be of larger diameters and the whole column of rings may appear of nearly the same diameter as in the instance observed by the author.

The preceding considerations suggest:

(1) Atmospheric vortex-rings systems are not likely to reveal themselves except in the early stages of formation of a vertically convective storm before the ring or rings have become obscured by vapor condensed by uplift of drier air through the core. If the upper air is abnormally dry a ring or system of rings may be projected to a considerable height before it becomes enveloped in cloud.

(2) In case of a succession of rings, when one ring is formed, it apparently brings about differential inertia effects between the air remaining beneath and above the cover layer, so that the cover layer vibrates up and down, producing a succession of surges and rings. This phenomenon is easily produced with a smoke-box by attaching a weight to the flexible cover so that when once disturbed, it vibrates back and forth for a time. When the vibrations become sufficiently slight, rings are not formed although there may still be an upward flow of moist air through the break in the cover layer.

(3) If it were possible to dissect flat-bottomed, fair weather, cumulus clouds, some might be found to contain vortex rings but many would not because of either (a) the lack of an appropriate cover layer and aperture, or (b) lack of a sufficiently strong, rapid impulse to develop a ring system.

Air circulation in thunderstorms and hailstorms

As early as 1875, John Wise [BLASIUS, 1875; SHAW, 1932] wrote a classical account of his experience trapped inside of a violent thunder and hailstorm during a balloon ascension. Wise tells how his balloon was carried toward and into a huge black cloud, apparently of circular form and four to six mi in diameter, how he found himself "whirling upward with a fearful rapidity, the balloon gyrating and the car describing a large circle in the cloud." Pelted by hail and snow, he was hurled rapidly upward, then violently surged downward, apparently some hundred feet. This happened eight or ten times, covering an interval of 20 min, until, finally, he was disgorged from the cloud and landed in a field in drenching rain. He noted the "violent convolutionary motion or action of the vapor cloud." Hardly could a more perfect description be given of the motion within a large vortex ring surrounding the core of a hailstorm.

An example of the formation of a tubular sheet vortex is easily observed but not always recognized in the case of dense smoke and steam ejected from the funnel of a locomotive when laboring heavily. In this case there is a series of successive impulses, each producing the ejection of a quantum of vapor and smoke and a vortex ring. This is not greatly unlike the more or less uniform gustiness of wind in a thunderstorm.

It can readily be shown that if ordinary turbulent flow of a fluid is considered as primarily laminar flow, on which is superposed resistance resulting from turbulence generated in the boundary layer in the form of vortex-ring systems transmitted into the interior of the flow, then 99.50 to 99.99 per cent of the energy available to produce translatory motion will be converted into vortex-ring energy and so will become latent in so far as producing motion of translation is concerned. Because of the relatively small resistance of laminar as compared with turbulent flow, the small remaining translatory energy suffices to produce the observed velocity of translation. In the case described, the energy entrained in the vortex rings is slowly dissipated as heat by viscous resitance within the fluid. This affects the velocity distribution but does not affect the mean velocity, which is determined by the amount of remaining translatory energy available. This is determined by conditions at the boundary and hence the rate or manner of dissipation of the latent energy of the vortex rings does not affect the mean velocity.

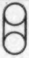
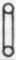
Experiments carried out by the author with a smoke-box having a round orifice at one end showed that the character of the vortex ring produced by a single impulse differed with the duration and sharpness of the impulse. A gentle pressure on the lid of the box lasting perhaps half a second produced a small vortex ring with outside diameter little greater than that of the orifice and a very small central opening or core diameter and a low velocity. A somewhat shorter, less prolonged impulse produced a larger ring with smaller torus section, larger core diameter and higher velocity. A sharp, short impulse produced a vortex ring with an extremely small torus and a core diameter about equal to the diameter of the orifice.

With a slow gentle impulse all the ejected fluid was entrained in the vortex ring. With stronger impulses, increasingly larger amounts of the ejected fluid remained separated from the ring as a part of the core, until finally, for a sharp, quick impulse, a large portion of the ejected fluid shot forward as a jet and only a small portion was entrained in the ring. These results are summarized in Table 1. In each case the ring traveled forward a certain distance at nearly a constant velocity and with a slight increase in diameter, then suddenly expanded to several times its original diameter, its forward motion stopped and the ring dissipated.

In each case similar experiments were carried out where, instead of a single ring, impulses of equal intensity and duration were produced as nearly as possible at uniform intervals, forming a chain of successive rings which approached each other as they traveled forward, and finally all came to rest at the same distance from the orifice. For slow, gradual impulses all of the

ejected fluid was contained in the rings, as shown on Figure 4A. For a succession of short, sharp impulses, the rings were so small and moved so rapidly as to be barely discernible but in view of the fact that most of the ejected smoke from the box remained in the core, there was formed virtually a steady stream or jet of fluid, as shown on Figure 4B. Except for extremely slow-moving rings the core diameter appeared to be nearly identical with the diameter of the rings. Assuming this to be the case and that the conditions are such that nearly the entire volume of ejected fluid is entrained in the ring, then a simple relation between the dimensions of the ring and its velocity as it leaves the orifice can be obtained as follows;

Table 1--Effect of impulse on vortex ring

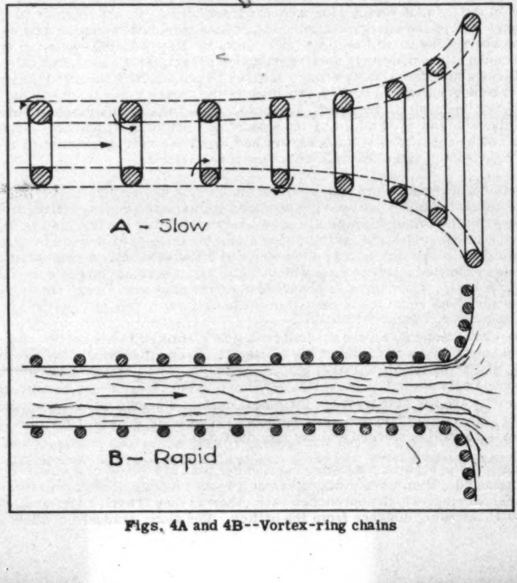
Impulse	Cross section	Core radius	Torus radius	Ejected fluid
Gradual		Small	Large	Goes into ring
Moderate		Medium	Medium	Mostly in ring
Quick		About same as aperture	Small	Mostly in core

Let V_j = volume of ejection or volume of ring; v_j = velocity of ejection through the orifice; t = duration of the impulse; r = core radius of the ring; and R = outer radius or torus. Then

$$V_j = \pi r^2 v_j t \quad (2)$$

Also

$$V_j = \pi(R + r) \cdot \pi[(R - r)/4]^2 \quad (3)$$



Figs. 4A and 4B--Vortex-ring chains

Let $\rho = R/r$. Equating (2) and (3) and solving for v_j gives

$$v_jt = \pi r\ (\rho^3 - \rho^2 - \rho + 1)/4 \quad \ldots\ldots\ldots\ldots \quad (4)$$

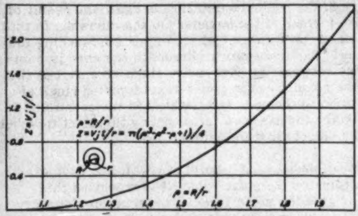
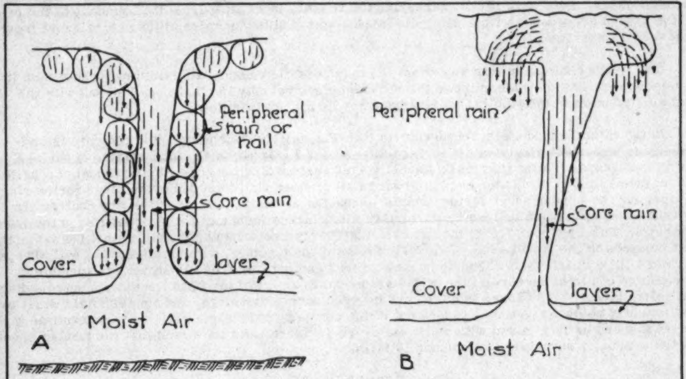


Fig. 5--Relation between ρ and Z

It can readily be shown that this equation has one real and two conjugate imaginary roots. Only the first of these roots need be considered. The value of this root can be expressed algebraically but for practical purposes it is more satisfactory to use a graphical solution. Figure 5 shows values of $\rho = R/r$ in terms of $z = v_jt/r$. For a given orifice radius r, and for the assumed conditions, the outer ring radiu R can be obtained from the strength and duration v_jt of the impulse. This curve gives results in accordance with the experimental results above described.

If a series of impulses or gusts occurs in a current of moist air flowing through a break in the cover layer, then the experiments described indicate that a varying range of conditions may result, as shown on Figure 6. For slow, prolonged impulses a tubular sheet vortex would be formed around an ascending core of air, as shown on Figure 6A, most of the moist air being contained in the vortex rings, which would gradually ascend and spread out at a certain height above the cover layer or orifice, at which height their energy is exhausted. For a series of short, sharp impulses, as shown on Figure 6B, most of the moist air would be contained in the ascending core and the surrounding chain of vortex rings or tubular sheet vortex would form a thin sheet or boundary of the ascending core. An infinite number of conditions can apparently exist. The conditions shown on Figure 6B are apparently those of most intense thunderstorms. Those occurring as shown on Figure 6A are much less usual and are probably those accompanying many hailstorms.



Figs. 6A and 6B--Thunderstorm models

Figure 6A represents a type of flow of one fluid through another which has not, so far as the author knows, been considered in hydraulic literature, and the laws and theory of its occurrence have not been fully determined. It can and apparently does occur under at least two natural conditions (1) In some thunderstorms, and (2) in some cases of density currents in lakes and reservoirs.

In case of turbulent flow in a pipe the resistance to flow occurs almost wholly in the boundary layer and results from the conversion of translatory energy into non-translatory or rotational energy of vortex rings. In this way most of the energy available to produce flow becomes in effect latent at the boundary. In case of a pipe the vortex rings are projected into the interior of the fluid current. For the conditions shown on Figure 2, the resistance to flow is again the result of translatory energy becoming latent in vortex rings formed at the boundary of the current. In this case there is no solid boundary and the vortex rings form a tubular sheet vortex surrounding the current and so remain outside of the region of flow. The translatory current in the core is composed wholly or chiefly of fluid drawn into the core between the successive rings as a part of the field circulation of the vortex system. Under these conditions the generation of vortex rings at the boundary has no effect on the velocity distribution in the core and the flow in the core is of a type in which the resistance and the mean velocity are the same as for ordinary turbulent flow but the velocity distribution within the core resembles closely that for laminar flow.

The mean velocity in a pipe represents the mean ordinate of a solid of revolution having as its base the cross-section of the pipe and as its ordinates the point velocities throughout this cross-section. So-called hydraulic slope formulas give the mean velocity in terms of slope S, hydraulic radius r/2, and roughness factor n. The formula now mostly used is that of Manning. which may be expressed in a form which is dimensionally sound,

$$v_m = (1.486/n)(r/2)^{2/3}\sqrt{S} \quad \dots\dots (5)$$

Also, the mean velocity is given by the equation

$$v_m = (1/\pi r^2)\int_0^r v_r 2\pi dr \quad \dots\dots (6)$$

Equating the two values of v_m and solving the resulting integral equation, an expression for velocity distribution or for v_r in terms of r can be obtained. Using the Manning formula this procedure leads to a law of velocity distribution closely resembling that for laminar flow, the velocity at the boundary being zero in both cases and the velocity increasing from the boundary to the center of the pipe in accordance with a parabolic law but with a different value at the central point from that for laminar flow.

The result obtained in this way is not the only possible velocity distribution. In this case it is a velocity distribution conforming to the required mean velocity for turbulent flow but with the velocity distribution in the pipe essentially the same as for laminar flow.

In the author's model of a thunderstorm (see Fig. 6B) the ascending air in the core is considered to be almost wholly moist surface air. A small fraction of the total volume of surface air is incorporated in the thin tubular sheet vortex surrounding the core. In the model of a hailstorm (see Fig. 6A), the ascending moist air is all or nearly all included in the large vortex rings comprising the tubular sheet vortex, and the ascending air in the core is either dry country air or this mixed with more or less moist surface air detached from and not incorporated in the vortex rings. The fluid comprising the field circulation need not be and generally is not the same as that comprising the vortex ring. Two vortex rings close together, with parallel axes, will always remain a little apart, even when one passes through another, as is easily shown by experiment. The source of air in the core in the hailstorm model is a part of the field circulation surrounding the vortex rings. This passes into the core between successive rings, and a mass of air equal to that entering below a given ring passes out of the core above the same ring. In the meantime it becomes more or less mixed with moist air carried upward, with the result that the tubular sheet vortex is usually enveloped in cloud and is invisible.

Part 2--Hail

Characteristics of hail--Hail is economically important, chiefly because of the damage it produces. While high rates of precipitation can and do occur in the form of hail, the author has not found an instance in which hail produced a serious flood, even on the small area over which it occurs. The time required for melting the hail reduces the rate of contribution of surface runoff to streams to less than the maximum for runoff from rain.

Hailstones have the following characteristics:
(1) Hail occurs in unusually violent, vertically convective storms.
(2) It usually occurs at or near the onset of the storm and in the early stages of its development.

(3) The precipitation of hail is usually of short duration, seldom more than a few minutes; there may be two hail periods, separated by a short interval of rain.

(4) Hailstones of various sizes occur in a given storm but there is often a particular size (sometimes two sizes) of hailstone which strongly predominate.

(5) Alternating layers of soft and hard ice comprising stones of a particular size have about the same diameters, forms, densities, sequence, and thickness.

Thus far atmospheric vortex-ring systems have been considered as a possible and probably not infrequent rheologic system accompanying convective storms. Whether such phenomena are of practical importance in dynamic meteorology remains to be determined.

The formation of hailstones is commonly attributed to water particles being carried upward through the hail and snow stages by a violent ascending air gust, then dropped out, caught at a lower level by another gust, and so on [HUMPHREYS, 1914]. Air currents accompanying vertically convective storms are subject to extreme gustiness. Aviators who have passed through such storms sometimes report losing and gaining height of more than a thousand feet at a time [ANONYMOUS, 1934]. Such examples of extreme bumpiness are commonly attributed to gustiness in an ascending air current. They are, however, equally well or better accounted for if the aviator happened to be caught in a ring vortex.

The ascending gusts in the tube-like core of a convective storm are neither uniform in intensity nor duration. Judged by gustiness at the ground level, they must be extremely irregular. Since the hail produced in a given storm is often mostly of uniform size, structure, and layering, it seems difficult if not impossible to explain the formation of such hailstones if they are the result of ordinary gustiness in an ascending air current. The height and velocity of ascent and descent would then be largely fortuitous, and hailstones of all sizes and with wide variations in character of layering would apparently result. References giving examples of hailstones of predominantly uniform size and structure follow.

ARENBERG [1938] describes a hailstorm at Washington, D. C., April 27, 1938, which the author also witnessed. This storm had the following features: Rain began 12^h30^m; small hail, hard ice 1/8 inch diameter, 12^h32^m to 12^h34^m; fragmental hail, one inch size predominating, 12^h37^m to 12^h54^m. These hailstones were unmistakably fragments of much larger hailstones and contained at least 12 thin concentric layers. The stones were mostly of conoidal shape and were evidently sectors of spheres two inches to three inches in diameter. The apex angles of the conoids (measured from photos) were about 60° and remarkably uniform. Arenberg gives calculations indicating that a large hailstone may be exploded by expansion of supercooled water on freezing. J. Schremp [ARENBERG, 1938, p. 277] suggests that fractures of the large hailstones may have resulted from atmospheric pressure waves generated by a nearby bolt of lightning. The form of the fragments is nearly that which would result from explosion by a central point charge in blasting homogeneous material. From the theory of blasting, this would produce conical fragments with a 45° slope or 90° central angle. If the material was less dense near the surface, the central angle would be smaller, as here observed.

ELLISON [1928] gives the following description of a hailstorm at Armagh, Northern Ireland, August 29, 1928: "But just before 15^h, the storm broke without any warning. It did not approach, but seemed to develop right overhead out of nothing at all. A few very large drops of rain, making splashes as big as pennies, then a flash, and a crash of thunder following instantaneously, and not rain but hail, in stones as big as nuts and marbles, fell in sheets.

"The storm lasted altogether less than an hour, but the greatest intensity lasted about 20 min. The rainfall, as recorded at the Observatory, was 1.69 inches in 50 min, of which one inch fell in the first 20 min. The trace of the Beckley recording rain-gage was so close that it was difficult to say whether it had emptied itself four or five times during that time. The amount collected in the Snowdon gage close beside it, however, agreed with the larger amount. The greater part of the precipitation being hail, the rate of fall must have been considerably greater than the gages indicated, as the funnels were nearly full of hail, which took some time to melt. There were two distinct forms of hailstones; small cones with hemispherical base, and spheres of clear ice. These were mixed in about equal proportions." The description is accompanied by a photograph showing "hail lying a foot deep in the roadway, The Mall, Armagh, August 29, 1928."

Large hail with a uniform layer structure occurred at Bagdad, April 24, 1930 [ANONYMOUS, 1930]. "At 14^h15^m, GMT, slight rain commenced, and at 14^h30^m the wind began to drop to calm and a heavy fall of hail occurred, continuing for seven minutes... An average specimen was cut open and found to consist of five layers of alternating hard transparent ice and soft white ice, arranged as follows: Core of hard transparent ice, 1/8 in diameter; layer of soft white ice, 1/4 in thick; layer of hard transparent ice, 1/8 in; layer of soft white ice, 1/4 in; and outer crust of hard transparent ice, 1/8 in. The total diameter was 1 5/8 inch, and in calm air the terminal velocity of hailstones of this size would be nearly 30 mi/hr. The descent of several specimens was actually timed against the wall of a building, and it was found that they fell 40 ft in about three sec, giving a velocity of only nine mi/hr. The low velocity of fall observed indicates an upward current of air of at least 21 mph."

Three hailstorms described by RUSSELL [1938] are as follows: "Baton Rouge, Louisiana, April 20, 1933, 21^h06^m to 21^h37^m; wind velocity 25 to 30 mph during the fall of the hail, dropping to nine mi/hr immediately afterward. In the 40 min following the hail one inch of rain fell, 0.35 inch in a single five-min interval. Two sharp rises of about 0.1 inch in barometric pressure occurred during and immediately after the hail. The hailstones were quite uniformly the size of golfballs and peculiar in their relative softness and simple structure. While seven bands were counted in one specimen, from three to five in several others, the typical stone had only a clear ice nucleus about one-half inch in diameter and a single coating of soft white ice surrounding it."

"Aurora, Illinois, May 2, 1933; ... the heavens showered the city with chunks of ice as big as oranges and in some instances even larger." Half an hour after the hailstorm there was a second violent thunderstorm, nearly two inches of rain falling within a brief space of a few minutes.

Ship Harbor, Nova Scotia, May 21, 1933; Hailstones "bigger than eggs ... roofs of 25 houses were riddled as by machine guns."

Behavior of a heavy particle in a ring vortex--The uniformity of successive concentric rings in hailstones in a given storm suggests strongly that they are not the result of mere haphazard circulation due to ordinary turbulence but rather are the result of some definite system of motion generally occurring somewhere in conjunction with uprushes of air which produce hailstorms. The requisite conditions are apparently provided by vortex rings surrounding the ascending core of air. An ordinary smoke ring comprises two components with a common system of motion (1) the invisible air molecules, (2) enormously larger smoke particles. Both types of particles are, however, of colloidal or sub-colloidal size, so they are held in suspension by the Brownian movement and are little subject to gravitational motion. An ordinary smoke ring does not differ greatly from a hydrodynamic scale-model of an atmospheric vortex ring, perhaps several miles in outer diameter, with a vortex diameter of the order of several hundred feet, the two components in this case being (1) air, as before, (2) snowflakes and hailstone nuclei, replacing the smoke particles.

Snow and minute solid ice particles are of course acted on by gravity and if they are in vertical rotation they are acted on by centrifugal force. The centrifugal force effect for small, light particles is, however, generally small compared with gravitation because of the large vortex radius r relative to the rotational velocity v. Centrifugal force is given by the equation $F = wv^2/gr$. Hailstones of ordinary sizes are so strongly acted on by gravity that it is doubtful if they partake of the circular rotation within the vortex ring.

Some idea of the behavior of a hailstone within a ring vortex may be obtained by considering what would happen if a very small, heavy, solid particle, such as a pebble, were dropped into an ordinary experimental smoke ring. If it is dropped into the ring on the outer side, its velocity will be increased by the downward velocity in the ring and it will fall through the ring with some acceleration. If it is dropped into the ring on the core side, its velocity will be decreased and it may either fall through the ring or, with a suitably high ascent velocity in the ring, it may be brought to rest and carried back upward. As illustrated by Figure 7, the pebble will be acted on by two forces (1) gravitation, (2) the impact of the gas forming the ring vortex and flowing against the pebble. The direction of this impact varies with the position of the pebble in the ring. If the pebble is near the bottom of the ring, on the core side, the impact velocity tends to deflect the pebble away from the center of the ring section. If the pebble is near the top of the ring section the force tends to deflect the pebble to the left (see Fig. 7) and it may be carried over the top and then dropped out. Apparently a solid object with a constant terminal velocity can make only a single circuit or loop in passing through the section of a ring vortex.

An alternative condition, where there is a series of successive vortex rings, one above another, is that a solid object, such as the pebble here considered, with a constant terminal velocity, could drop from one ring to another, passing through a loop-like orbit within each successive ring, thus providing a series of alternate uplifts and descents, in each of which, in case of a hailstone, a pair of layers of hard and soft ice could be formed. This, however, is not believed to be the usual condition of formation of hailstones. It is a condition which can and probably does occur if the ring sections are of equal diameter and one below another. The distance the stone would fall in passing through different rings would not vary greatly and the result might be a series of alternate layers of soft and hard ice, the number of such layers being equal to the number of successive rings surrounding the vertically ascending core of air.

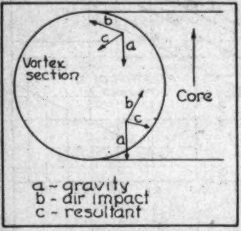


Fig. 7--Forces acting on a solid particle dropping through a ring vortex

Terminal velocities of hailstones--Using drag coefficients derived by towing spheres behind an airplane and equating the force with the resistance, **BILHAM** and **RELF** [1937] determined the terminal velocities for spherical hailstones of different diameters and densities by use of the equation

$$v_t = \sqrt{2\alpha g d/3\rho k_d} \quad \ldots\ldots\ldots\ldots\ldots \quad (7)$$

d = diameter, in ft; α = density of hailstone, lb/ft^3; ρ = density of air, lb/ft^3; k_d = drag coefficient; R = Reynolds number = v_t/γ; v_t = terminal velocity, ft/sec, relative to air stream; γ = kinematic viscosity of air. Since the terminal velocity v_t is also the velocity of the ascending air current required to hold the hailstone in suspension, it may also be referred to as the suspension velocity. The terminal velocity v_t depends on the drag coefficient k_d and this depends on Reynolds number R and on the velocity. Consequently (7) must be solved by trial except for diameters less than 1.5 inches, for which k_d is sensibly constant and equal to 0.25. Bilham and Relf give terminal velocities for different densities, using, for air, γ = kinematic viscosity = 0.000159; ρ = density of air = 0.0758 lb/ft^3, and with values of k_d as shown in Table 2. For

Table 2--Relationship of Reynolds number to drag coefficient

$R/10^5$	0	1	2	3	4	5	6	7
k_d	0.250	0.248	0.240	0.225	0.055	0.035	0.036	0.037

Reynolds number R between 3×10^5 and 4×10^5 the drag coefficient k_d drops off abruptly with change of regime of flow from laminar to turbulent. The terminal velocity increases abruptly for the critical diameter of hailstone to more than double its value for slightly smaller diameters.

Because of this change of flow regime, a hailstone which has grown to 4.8 inches in diameter will always fall, since to sustain it would require an ascending air current with a velocity of nearly 400 ft/sec. Bilham and Relf's calculated terminal velocities for different densities are accurately represented by the lines on Figure 8 and by the simple empirical formula there given. These are for surface conditions. For conditions at 10,000 ft elevation the terminal velocities are increased 15 per cent.

Alternating terminal velocities--As a hailstone grows, taking on alternate layers of high and low density ice, its terminal velocity will alternately increase and decrease for suitable conditions of density and layering. If the initial diameter and density of a hailstone are d_1 and ρ_1, and its density ρ_2 after the addition of a layer of ice of density ρ', increasing its diameter to d_2, then

$$\rho_2 = [d_1^3\, \rho_1 + (d_2^3 - d_1^3)\, \rho']/d_2^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

Diameters are in inches and densities are relative to water.

Assuming a hailstone with layering as in the example given above, the densities after addition of successive layers, using ρ' = 0.9 for hard ice and ρ' = 0.25 for snow ice, layers, the corresponding terminal velocities are as shown in Table 3. After the first soft layer is added, the terminal velocity decreases with the addition of each successive low density layer. This suggests the possibility of the necessary alternations of hailstone velocity relative to that of the air current taking place in a steadily ascending air current without invoking gustiness as shown by the last column of Table 3. In this case the hailstone would continually ascend but at alternating higher and lower velocities relative to the air stream. If the accretion rate were proportional to the relative velocity, then the thicknesses of layers of either type of ice would be relatively constant and a large number of hailstones having the same or nearly the same structure and diameters would result. The steady flow conditions favoring this result certainly do not ordinarily exist in the core of a vertically convective storm.

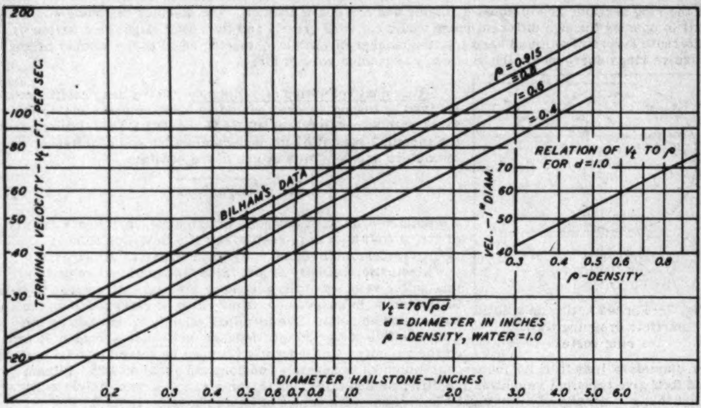


Fig. 8--Terminal velocity in ft/sec of spherical hailstones; Bilham's data, Q. J. R. Met. Soc., April 1937, p. 153, surface conditions

Table 3--Variation of density and terminal velocities

Layer	ρ'	d_1	d_2	ρ_2	v_t	Ascent velocity[a]
		in	in		ft/sec	ft/sec
1	0.90	0	0.125	0.90	25.5	44.5
2	0.25	0.125	0.625	0.255	30.3	39.7
3	0.90	0.625	0.875	0.668	58.1	11.9
4	0.25	0.875	1.375	0.357	53.4	16.6
5	0.90	1.375	1.625	0.529	70.3	- 0.3

[a] In a uniformly ascending air current with a velocity of 70 ft/sec.

The formation of hailstones in ring vortices

Gustiness, in the ordinary sense, is unquestionably much less pronounced in a ring vortex surrounding an ascending core of air than within the core. This results from various causes and can be proven experimentally by projecting a smoke ring through turbulent, smoky air. The ring may pass through the turbulence with apparently little effect. It appears that the combination of alternating terminal velocities, in conjunction with the air circulation in a vortex ring, provides the requisite conditions for the formation of large numbers of hailstones of similar sizes and characteristics.

A hailstone nucleus may originate at any point within the section of a ring vortex, as at p′, in Figure 9. Initially, it is so small that it may be carried around with the vortex in a nearly circular path but as it grows in size its terminal velocity increases until, when it reaches the point marked 1 on Figure 10, the vertical component of air velocity is insufficient to sustain it and it falls to point 2, taking on a layer of low-density ice as it falls, with a resulting decrease in its terminal velocity, so that at the point 2 the vertical component of rotational vortex velocity is again sufficient to sustain it and it starts a second upward course. Successive loops in the path of a hailstone may be somewhat as illustrated schematically by Figure 9. Finally, when the hailstone reaches sufficient size so that its terminal velocity exceeds the vertical component of vortex velocity at the lower point of its descent, it falls out of the vortex to the ground.

The determination of the equation of the looped spiral orbit of a growing hailstone enveloped by a vortex ring presents an interesting problem in mathematical physics, involving physics, physical chemistry, fluid and solid dynamics, thermodynamics, and some as yet unsolved problems concerning

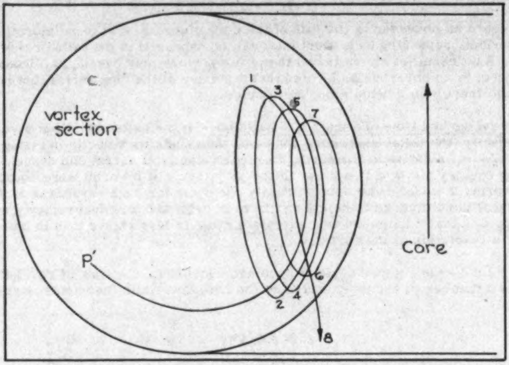


Fig. 9--Hailstone circulation in a vortex ring (schematic)

the laws of condensation, particularly the effect of wind on rate of condensation. At a given position in the vortex section a hailstone which has fallen far enough to attain its terminal velocity will have the following velocities; where r' is the distance from the center of the vortex filament to the center of the hailstone.

$$\text{Falling velocity} = v_t + v_a r'/r \quad \dots\dots \quad (9)$$

$$\text{Ascent velocity} = v_t - v_a r'/r \quad \dots\dots \quad (10)$$

$$\text{Time of ascent/Time of fall} = (v_t + v_a r'/r)/(v_t - v_a r'/r) \quad \dots\dots \quad (11)$$

The last equation shows that the time of ascent will be greater, often much greater, than the time of fall, in executing a given cycle.

No assumption has been made as to the manner in which accretion occurs and hailstones grow in size. Authors are not in agreement either as to this [SCHUMANN, 1938] nor are they in agreement as to the temperature of a hailstone relative to that of the surrounding air. A hailstone is not cooled or heated in rising or falling, as much as the air, and it seems clear that at the top of a cycle a hailstone is warmer relative to the surrounding air than when at the bottom of a cycle. Its temperature may be and probably is below freezing in both locations. VON HANN [1926] states that the temperature of hailstones, measured immediately after their fall, is often much below 0°C and can reach from -5 to -15°C.

It is assumed that a hailstone forms a hard ice layer in ascent and a softer ice or snow-ice layer in descent.

It will be seen that small hailstone nuclei are quite certain to be carried over the top in their first circuit within a ring vortex and will then fall to the ground either as graupel (soft hail) or, after melting, as rain, while larger nuclei will in general form hailstones, whatever may be their point of origin within the ring vortex.

Calculations above given are based on an assumed density of 0.25 for soft ice accretion during descent. Probably the newly added material if in the form of ordinary snowflakes will have initially a density 0.1 instead of 0.25, as assumed in Table 3. The terminal velocity during descent may then drop off rapidly and only a relatively small vertical velocity component will be required to start the hailstone on another upward course. Each soft layer therefore will become consolidated more and more as new layers are added.

It is to be remembered that when thick rings are formed, nearly all of the ejected moist air goes into and remains in the rings. The core and surrounding field are constituted of drier air. Apparently hail is not likely to form in both the core and the vortex in the same storm.

With respect to an observer in the path of the core of a ring-vortex hailstorm, hail should occur in two periods, separated by a short interval, as happened in the hailstorm of April 27, 1938, at Washington. As a result of storm travel these two periods may overlap, affording continuous hail. With respect to an observer so located that a portion of the ring vortex, but not the core, passes over him, there would be only one hail period.

Number of cycles and time of ascent of a hailstone--If the hailstone fell at a velocity equal to its terminal velocity, the latter remaining constant, then since its velocity in rising is $v_t - v_a$, and in falling, $v_t + v_a$, relative to the earth, its mean velocity of ascent and descent relative to the surrounding country air would be zero. If the major axis of its orbit were equal to the diameter of the vortex it would make approximately one cycle for each revolution of the vortex. Variations of these conditions as to height and form of orbit and terminal velocity will alter this result and it appears that a hailstone will execute a cycle in less rather than in more time than is required for a revolution of the vortex.

If the gross time required per cycle is assumed equal to t_r, the time of revolution of the vortex, then the least number of cycles executed by the hailstone while the vortex is rising through a height h will be

$$N = h/4\pi r \quad \text{.......................} \quad (12)$$

and the least time of suspension will be

$$T = h/v_a \quad \text{.........................} \quad (13)$$

For example, taking $h = 31,480$ ft, which is about the maximum, and $r = 500$ ft, a hailstone will pass through at least five cycles in rising, and if $v_a = 50$ fps, the time of suspension $T = 10.4$ min. The core of the vortex will rise through the same height in one-half of this time or 5.2 min. Actually the time of ring ascent will always be greater than these figures indicate, for two reasons: (1) The ring velocity r is governed by the velocity at the outer surface of the core. This will always be smaller than (usually about two-thirds) the mean velocity v_a of the core. (2) The ring velocity will be reduced by the effect of the downward velocity of the field and so will be less than one-half of the peripheral velocity of the ring.

It will be seen that the ascent velocity of the vortex ring is always less than one-half the ascent velocity at the periphery of the core and still smaller relative to the mean ascent velocity of the core. A ring vortex provides both the high velocity of ascent at the position of the hailstone, required for suspension of large hail, and the considerable duration of the process of hail formation which seems necessary in case of large hailstones.

Whatever may be the manner of growth of a hailstone, whether by condensation of vapor, absorption of cloud particles or by accretion of supercooled raindrops or snowflakes, some idea of the travel distance and time required for the growth of a hailstone may be obtained by a simple method used by SCHUMANN [1938].

If m is the water concentration in the air, grams/cc, including vapor, liquid, and frozen water, and z is the fraction of the total water encountered by the hailstone in its path which is absorbed or condensed on the hailstone, then Schumann's analysis shows that the distance S which the hailstone must travel relative to the air to sweep up sufficient water to give it a radius R, in cm, is given by the formula

$$S = \rho\,(4R - 1)/zm \quad \text{.......................} \quad (14)$$

where ρ is the density of the hailstone, grams/cc. Assuming that the hailstone grew by condensation of vapor and that all the vapor in its path was taken up, and with $m = 5 \times 10^{-6}$ and $\rho = 0.6$, starting with a stone 1/4 cm in diameter, S = 16 km. Schumann states that the maximum value of m for vapor is 6 to 7×10^{-6}, grams/cc, but believes the high-rain intensities indicate that raindrops in suspension may increase this to as much as 38×10^{-6}.

Schumann also studied the time required for the growth of a hailstone and concludes: "that there must either be extraordinarily high concentrations of condensed water or that there must be extremely violent up-currents to maintain the hailstone for a sufficient length of time in the environment favorable to its growth."

Limiting conditions of hailstone formation--BILHAM and RELF'S [1937] analysis leads to the result that hailstones over 4.8 inches in diameter cannot form, but only for the reason that when this size is attained, their suspension velocity is quite suddenly increased, so that it would require an ascending air current of over 200 ft/sec to sustain them. Authentic hailstones of over four inches diameter are on record, also fragmentary stones with radii indicating that the parent stone was over four inches in diameter.

The peripheral velocity of a vortex filament or the surface velocity of the core must at least equal the suspension velocity of the hailstone in order to permit a stone of a given diameter to form. BUELL [1943] has given an equation for the maximum ascent velocity in the cumulus-congestus in a convective storm in terms of the height J in millibars of the barometric jump at the onset of the storm. Buell's equation can be reduced to the form

$$v_g = 43\sqrt{J} \qquad (15)$$

in ft/sec. From Figure 8

$$v_t = 76\sqrt{\rho d} \qquad (16)$$

Equating v_g and v_t gives

$$J = 3.13\,\rho d \qquad (17)$$

for J in millibars, d in inches, and ρ = unity for water.

Table 4 shows the calculated terminal velocities v_t and J for hailstones of a density of 0.6 and of different diameters.

Table 4--Terminal velocities and barometric jump for hailstones of density 0.6, for different diameters

Diameter	v_t	J
in	ft/sec	mb
0.5	41.3	0.94
1.0	58.4	1.88
1.5	71.2	2.82
2.0	82.3	3.76
2.5	92.3	4.70
3.0	101.0	5.64
3.5	109.2	6.58
4.0	116.8	7.52
4.5	123.8	8.46

For the conditions shown in the table it would require an ascent velocity of 82 ft/sec and a barometric jump of 3.76 mb to produce a hailstone two inches in diameter, and an ascent velocity of 124 ft/sec and a barometric jump of 8.46 mb to produce a hailstone of approximately the limiting diameter. These results while approximate are apparently of the right order, and the simple relation given by this equation indicates that the maximum diameter of a hailstone which can be produced in a given storm is in direct proportion to the height of the barometric jump. The equation gives an indication of the size of hail which can be formed in a given storm in terms of the quantity J, which can be directly measured at the ground surface. Comparison of these results with observed sizes of hailstones and values of J have not been made.

The observed fact that hailstones are often fragments of initially much larger hailstones indicates that when hail forms, many of the hailstones grow to the maximum possible size for the given conditions. This is in accordance with the expected result if hailstones are formed in ring vortices but not if they are the result of accidental or fortuitous gustiness. Apparently most but not all hailstones which grow nearly to the maximum possible size explode but some do not. In the Washington storm, for example, hailstones over two inches in diameter were observed in the outskirts of the city [ARENBERG, 1938].

BROOKS [1944] has analyzed data on hailstone sizes from Hailstorms in India [ELLIOTT, 1899]. Brooks gives an equation for the number of stones in all storms having diameters equal to or exceeding d inches. Brooks' equation in terms of relative frequency is

$$F_r = (0.295)^d \qquad (18)$$

Let 0.295 = a and $a^d = e^{-kd}$. Then $d \log_e a = -kd$ and $k = -\log_e a = 1.22$.

As an inverse exponential function

$$F_r = e^{-1.22d} \qquad (19)$$

where F_r is the fraction of the total (taken as unity) or exceeding a given time.

The integral frequency below size d is $1 - F_r$. The relative frequency for a given size is obtained by the differentiation of $(1 - F_r)$ or

$$f = 1.22\, e^{-1.22d} \qquad (20)$$

Solving (20) for f = 1.0 gives d = 0.0164 mm as the smallest size of hailstone included in the data. The data used were from 507 samples in hailstorms which occurred in India from 1833 to 1899 and the frequency distribution is the relative frequency of hailstones of different sizes in different storms but not in the same storm. Agreement between observed and computed frequencies is nearly perfect for hailstone diameters less than 1.5 inches. For larger diameters the observed number of hailstones is greater than the computed number, as would be expected if many of the hailstones were initially of large diameters and a large fraction of the smaller stones, which chiefly determine the form of the frequency curve, were produced by fragmentation.

Maximum precipitation intensity as hail--As already noted, all of the moist air ejected through the cover layer in the formation of an atmospheric ring vortex goes into the vortex ring. A ring or succession of rings is therefore capable of producing as much precipitation as could be produced under otherwise similar conditions in a vertically convective storm of the tubular type. One cubic meter of saturated air at 32°F contains 4.8 gm of water vapor, of which perhaps 4.5 gms is precipitable. A ring vortex with torus radius of 2000 m and vortex radius of 200 m contains a volume of approximately 1.6×10^9 m^3, which, when saturated at 32°F contains about 7.2×10^9 gms of precipitable water vapor. This would produce a precipitation depth of 0.047 cm over 152×10^9 sq cm an area equal to a circle having a diameter equal to the outer diameter of the ring. A numb n of successive rings would produce n times this amount.

The maximum recorded rainfall for short intervals is given by the equation [U. S. WEATHER BUREAU, 1941] $P = \sqrt{t}$, where t is time in minutes and P is rainfall in inches. This equation applies only for time intervals of one to 15 min and tropical or subtropical locations near sea level. For t = one min, P = one inch; for t = five min, P = 2.24 inches; and for t = ten min, P = 3.16 inches.

The number of hailstones per sq ft of diameter d, in inches, required to produce one inche of water, is given by the equation

$$N_1 = 275/\rho d^3 \qquad (21)$$

The number N per sq ft/sec required to produce a precipitation intensity of one inch per hour is

$$N = N_1/3600 = 0.0764/\rho d^3 \qquad (22)$$

For density $\rho = 0.6$ these formulas give the values shown in Table 5. Since it requires only one hailstone one-half inch in diameter per sec per sq ft to produce a precipitation intensity of one inch per hour, a comparison of these figures with observed maximum rain intensities indicates that hail may be capable of producing higher precipitation intensities than are ever observed from the fall of rain.

Table 5--Values of N_1 and N for various values of diameter

d	N_1	N
in		
0.5	3667	1.02
1.0	458	0.127
1.5	136	0.0378
2.0	58	0.0161
3.0	17	0.00472
4.0	7.2	0.002

The funnels of non-recording and tipping bucket recording rain gages are usually completely blocked by hail and no record of true intensity of precipitation is obtained. The question is therefore open whether hail or rain produces greater intensities. Hail is, of course, always precipitation from suspension storage. The question is of some interest in relation to derivation of equations for maximum rain intensity, which are much used by engineers in the design of storm-sewers, airport drainage, and other works.

Conclusions

(1) Atmospheric vortex-ring systems occur in conjunction with violent convective storms. When they occur the ascending moist air is concentrated in the vortex rings.

(2) The conditions favorable for the occurrence of convective vortex-ring systems are also favorable for the production of hailstorms.

(3) Hailstorms are apparently of two types: (a) Where the hail is formed in an ascending current of moist air and results from gustiness. Such storms are likely to produce hailstones of various forms, sizes, and different internal structures but not generally of maximum sizes. (b) Storms where the hail is formed in ring vortices. Such storms are likely to produce hailstones of maximum sizes, and fragmental hailstones and frequently a large proportion of the hailstones will be relatively uniform in size and internal structure.

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RADIOLOGICAL AND SALINITY RELATIONSHIPS IN THE WATER AT BIKINI ATOLL

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Abstract--The circulation in Bikini Lagoon during the post-Baker Day period is deduced from the distribution of salinity and radioactivity. The use of the distribution of radioactivity as a method of determining the circulation is compared with other methods. The presence of radioactivity in the waters of the Lagoon as a result of the explosion presented a unique opportunity to obtain a partial evaluation of the radioactive tracer technique in problems of hydrography.

Figures showing a circulation scheme and the distribution of salinity and radioactivity are presented for the third, fourth, and fifth day after the underwater explosion. The circulation at this time was found to be abnormal due mainly to the unusual weather conditions. It has therefore been discussed with particular reference to the areas of concentration of the radioactive material in view of the possible bearing on studies of the effect of radiological contamination on marine flora and fauna at Bikini.

The use of radioactivity in tracing water motions at Bikini gave results which were in general agreement with those obtained by other methods.

Introduction--In this paper, the circulation of the waters of Bikini Lagoon in the period following the underwater explosion of the atom bomb is deduced from the distribution patterns of salinity and radioactivity, and the use of the distribution of radioactivity as a method of determining the circulation is compared with other methods. The presence of radioactivity in the waters of the Lagoon as a result of the explosion presented a unique opportunity to obtain a partial evaluation of the radioactive tracer technique in problems of hydrography.

The water samples upon which the radiological data are based were taken at the same time as the salinity samples, thus providing two independent but simultaneous methods for the study of the circulation system.

During the several months of field research at Bikini, considerable salinity data from both the Lagoon and surrounding ocean waters were obtained which showed that substantial salinity variations occurred within short periods of time, not only in the neighboring ocean surface waters, but also within the waters of the Lagoon. These variations throw light upon the exchange of water between the Ocean and the Lagoon and upon the circulation of the Lagoon itself. In this paper, consideration of these effects is largely confined to the post-Baker Day period; that is, to the period following the underwater atom bomb blast when they were of particular interest in connection with the dissipation of radioactive material. Baker Day was July 25, 1946, Bikini time.

Data--Water samples for both salinity and radiological analyses were obtained with the conventional Nansen bottle, and where both types of analysis were required they were taken from the same bottle, thus assuring an identical source. Surface samples were normally taken by bucket. Depths of sampling were determined by a metering wheel.

The salinity samples were analyzed within a few days of collection, and the radiological samples usually within 24 hr. Salinity was determined by the KNUDSEN [1946] method with an error not exceeding ± 0.03 o/oo. Radiological analyses were performed aboard the USS Haven under the supervision of K. G. Scott and G. C. Ewing. The units of activity are only relative; the actual units were not provided with these data for reasons of security. All measured activities have been calculated back to a standard time after the explosion in order to eliminate the complication of the radioactive decay rate. Although counts of less than 0.01 units of activity were recorded, values of less than 0.1 are in general treated as zero in this paper.

Discussion and results

Lagoon salinity changes and circulation--The normal circulation within the Lagoon and the rate of exchange with the ocean have been described by VON ARX [1948]. The observations were made under typical spring conditions and they show, among other things, that Enyu Channel, despite its size, was a relatively unimportant passage for exchange between ocean and lagoon waters. With the advance of summer, evidence accumulated that the influx of ocean water through Enyu Channel became a dominating feature. A review of salinity data now available indicates that the influx was not a simple flow subject to tidal variations, but from time to time became a substantial intrusion over and above normal flow. At least three such intrusions appeared to have occured during May, June, and July; in this paper only the intrusions which were in evidence to a marked and well-defined degree in the week including Baker Day are discussed.

Surface samples from representative points in the Lagoon were taken between 15 and 21 July (see Fig. 1). The average salinity was found to be 34.59o/oo and the surface was practically isohaline from end to end. This being so, and since the average wind velocity was 12 knots, it was probable, on the basis of previous experience, that the water was also isohaline vertically. Outside surveys made at the same time (see Fig. 2) revealed the presence of water with salinity less than 34.30 ⁰/oo just a few miles to the south of the Atoll and water of greater than 34.60 ⁰/oo along the northern edge of the Lagoon. Earlier outside hydrographic cruises had also revealed the recurring presence of tongues or eddies in the upper 150 ft of the neighboring ocean waters whose salinity differed significantly from that in the Lagoon.

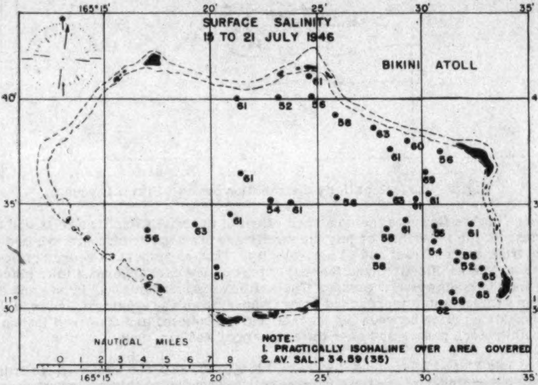
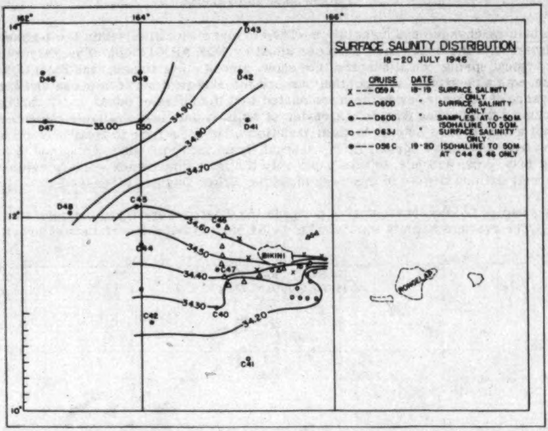


Fig. 1--Surface salinity in Bikini Lagoon for week ending July 21, 1946; average salinity, 34.59 ⁰/oo for 35 observations, with little variation from the mean; the numbers alongside the dots are (observed salinity, 34.00 ⁰/oo) × 100

Following Baker Day, on July 28, 29, and 30, water samples were taken at depths of 0, 10, 75, and 150 ft at many points in the Lagoon. The results are plotted to show surface and vertical distribution in Figures 3 to 12. These surveys revealed that a marked change in the salinity distribution had occurred since the survey of the week preceding, and that the vertical structure was characterized by a thin surface layer of high salinity water in the central area, a layer of lower salinity varying in thickness from 50 to 150 ft underlying the surface and extending almost throughout the Lagoon, and finally by higher salinity in the deeper water.

This situation implies that the circulation system of the Lagoon differed in important aspects from the normal circulation that exists in the spring, since in none of the previous salinity surveys extending back four months had any such vertical structure been found. Influx of water over the eastern and northern reefs was reduced to a small fraction of the flow characteristic of spring.


162°
164°
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SURFACE SALINITY DISTRIBUTION
18-20 JULY 1946
CRUISE DATE
x ---059A 18-19 SURFACE SALINITY ONLY
△---0600 " SURFACE SALINITY ONLY
●---0600 " SAMPLES AT 0-50M. ISOHALINE TO 50M.
○---063J " SURFACE SALINITY ONLY
●---056C 19-20 ISOHALINE TO 50M AT C44 & 46 ONLY
D43
D46
D49
D42
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35.00
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BIKINI
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C40
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C41
RONGELAP

Fig. 2--Surface salinity distribution outside Bikini Lagoon

The driving force of this flow was the combined effect of the North Pacific swells and the strong northeast trades. In the latter half of July the swells had practically disappeared, and the wind was frequently from south of east and of low velocity. Thus an important source of new water for the Lagoon was no longer effective, and the major part of any exchange must take place through Enyu Channel and the southwestern passes. The salinity distribution, both inside and out, indicates that lower salinity water approached Enyu Channel from the southeast, entered the Lagoon, took an intermediate position between the surface and the bottom, and displaced lagoon water through the southwestern passes and over the submerged western reefs.

The wind of July 22 to 27 averaged six knots, blowing for two consecutive days from south-southeast, and the remainder of the time from east. The south-southeast wind, though very light (five knots), undoubtedly aided the inward flow across Enyu Channel.

Enyu Channel is of such size that an average inward flow of 0.5 knots would renew about one-half of the lagoon water in four days. It is estimated that during the seven days preceding July 28, 40 per cent of the lagoon water was displaced by lower salinity ocean water. This figure is based on an initial average salinity of 34.59 ⁰/oo, a final average of 34.50 ⁰/oo, and a salinity of 34.35 ⁰/oo for the source water outside. If all of this water had entered through Enyu Channel, a net inward current of only 0.25 knots would be required.

A complex but interesting situation existed in the central part of the Lagoon in the post-Baker Day period which throws additional light on inward flow through Enyu Channel. The surface distribution of salinity, as given in Figures 3, 4, and 5, shows the development of a low salinity trough on July 29 extending from Enyu Channel to the center of the Lagoon. Only the remnants of a trough are visible on July 30. North-south sectional views through the central area (see Fig. 6, 7, and 8) show the nature of the situation perhaps a little more clearly. (The positions of the sections are shown in Fig. 3, 4, and 5). Section A for July 28 (see Fig. 6), shows a surface layer with a salinity greater than 34.50 ⁰/oo extending at least two-thirds of the distance across the Lagoon from the north. By July 29, this surface layer had disappeared except for a patch adjacent to the southern islands. On July 30 (see Fig. 8), the 34.50 ⁰/oo surface layer had reappeared in a form similar to that of July 28, but thinner. Section C for July 30 (west-east axis of the Lagoon: see Fig. 9) shows a low salinity pocket (less than 34.40 ⁰/oo) located some three miles west of its apparent position the day before. To complete the picture, profiles, which run parallel to and one mile inside of Enyu Channel, are presented for July 29 and 30 (see Fig. 10 and 11). On July 29, a well-defined low salinity pocket was located in the middle of the Channel. Twenty-four hours later, it had largely degenerated. To sum up, it would appear that in the space of less than 48 hr a mass of water of salinity less than 34.40 °/oo entered at about the middle of Enyu Channel and traveled approximately nine miles into the west-central part of the lagoon. The pocket extended down from the surface roughly 75 ft and was perhaps two miles wide. The average velocity of the pocket, 0.5 knots, in terms of spring conditions, would not be surprising, but is remarkable at this time in view of the sluggishness of the circulation elsewhere. The phenomenon indicates again that the Lagoon was subject to intrusion of ocean water across Enyu Channel and illustrates the extraordinary nature of the circulation pattern during the latter part of July.

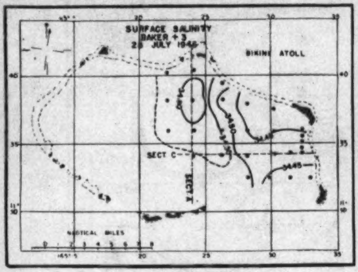


Fig. 3--Surface salinity in Bikini Lagoon, July 28, 1946

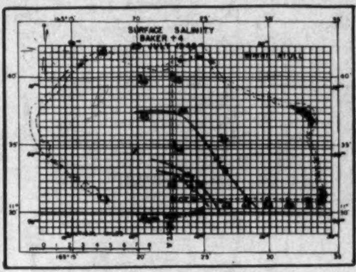


Fig. 4--Surface salinity in Bikini Lagoon, July 29, 1946; the grid, used for locating positions within the Lagoon, is also shown

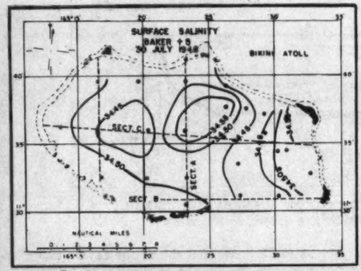
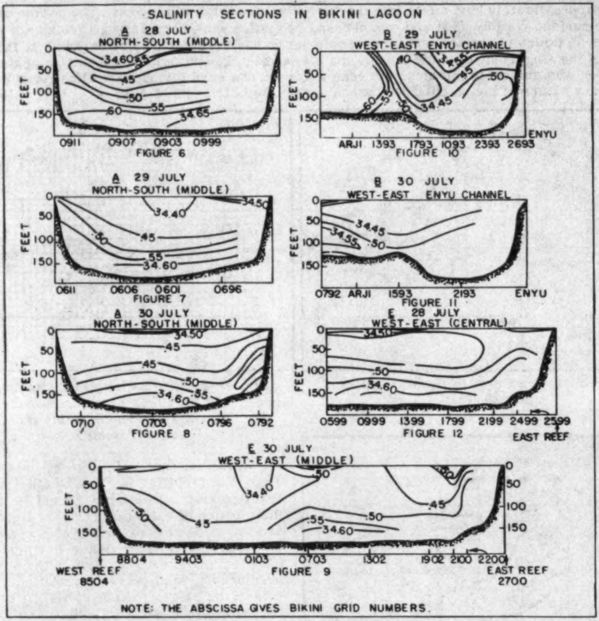


Fig. 5--Surface salinity in Bikini Lagoon, July 30, 1946

A further insight into the circulation of the Lagoon at this time is given by other changes that occurred between July 28 and 30 in the distribution of salinity. The very light winds and intrusion of ocean water of lower salinity that characterized the Baker-Day period must have led to a great reduction in the normal overturning, wind-driven circulation. The return of the easterly winds at velocities above ten knots on and after July 28 tended to reestablish the normal current system. A comparison of Figures 3 and 5 shows that the water in the lee of Bikini which had a low surface salinity moved westward, with the development of a current along the northeast reef and a broad band of higher salinity water along the eastern reef. This water originated in the return bottom current which upwelled in the eastern end of the lagoon. The development of this upwelling zone is illustrated by comparing the sharp upward swing of the isohalines near the east reef on July 30 (see Fig. 9) with those on July 28 (see Fig. 12). If the edge of the upwelling zone is defined as the position of upsweep of the isohalines, this would place the edge about 4000 yd from the midpoint of the east reef. This agrees closely with the estimate derived from the distribution of radioactivity.

Radioactivity as a tracer for the circulation of lagoon water--The lagoon circulation may also be deduced from the distribution of radioactivity, and the results compared with those based on direct current measurements, model studies, and salinity distribution. The activity data has been plotted in terms of iso-activity contours at three levels, surface to ten ft, 75 ft, and 150 ft, for July 28, 29, and 30 (see Fig. 13 to 21). A consideration of these contours which follows reveals that not only do the radiological data give a picture of the circulation of the Lagoon which is in general agreement with that deduced by other methods, but they give more detailed information than did the salinity observations. This may be largely attributed to the fact that the activity was moving from a source of high concentration to areas of low concentration, while, on the other hand, salinity differences at Bikini were very small, often being only two or three times the experimental error.



NOTE: THE ABSCISSA GIVES BIKINI GRID NUMBERS.

Fig. 6-12--Salinity sections in Bikini Lagoon; the abscissa gives Bikini grid numbers, the positions of which are shown in Figure 4

The changes in the activity distributions from July 29 to 30 show that the upper layer (down to at least 75 ft) of the lagoon water in the northwest was moving westward at about 0.15 knots (compare Fig. 16 to 21). In the central part, the surface iso-activity lines had moved farther west than those at 75 ft, indicating thereby that the 75-ft level in this area was in the transition zone between the surface and bottom currents, and that the surface layer became thinner toward the eastern end of the lagoon. The deep water is shown to have been moving in a generally eastward direction as a return current, since no appreciable activity was found at 150 ft except in the region of upwelling along the eastern reef and in an isolated patch extending south from Amen Island. The region of upwelling is quite well defined by the fact that the positions of the iso-activity contours at 75 ft correspond closely with those of the 150-ft level (see Fig. 20 and 21). Evidence of the sinking that would be expected in the western end of the Lagoon is shown by the significant amount of activity found from surface to bottom in that area (see Fig. 19, 20, and 21), while somewhat farther east the activity near the bottom was zero. These aspects of the circulation pattern as of July 30 are in general agreement with the basic lagoon circulation described by Von Arx, and are summarized in a current diagram (see Fig. 22). However, there are marked deviations which will now be examined.

The upper 75 ft (at least) of the lagoon water was divided into two systems during the period under consideration (July 28 to 30) by a rather narrow dividing zone running northwest from Enyu Island (see Fig. 19). The northern system contained the activity, the remaining area being virtually uncontaminated. There was no movement of the activity across this zone of demarcation except in the western half of the lagoon, despite the prevailing easterly wind. Two

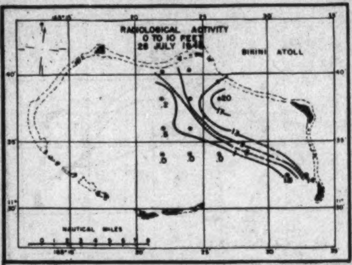

RADIOLOGICAL ACTIVITY
0 TO 10 FEET
28 JULY 1946
BIKINI ATOLL
NAUTICAL MILES

Fig. 13--Radiological activity in Bikini Lagoon, 0 to 10 ft, July 28, 1946

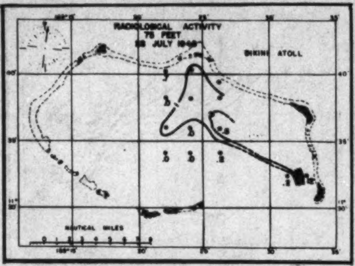

RADIOLOGICAL ACTIVITY
75 FEET
28 JULY 1946
BIKINI ATOLL
NAUTICAL MILES

Fig. 14--Radiological activity in Bikini Lagoon, 75 ft, July 28, 1946

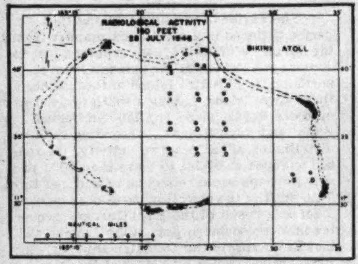

RADIOLOGICAL ACTIVITY
150 FEET
28 JULY 1946
BIKINI ATOLL
NAUTICAL MILES

Fig. 15--Radiological activity in Bikini Lagoon, 150 ft, July 28, 1946

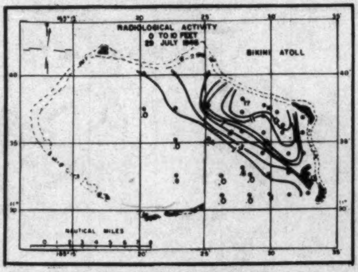

RADIOLOGICAL ACTIVITY
0 TO 10 FEET
29 JULY 1946
BIKINI ATOLL
NAUTICAL MILES

Fig. 16--Radiological activity in Bikini Lagoon, 0 to 10 ft, July 29, 1946

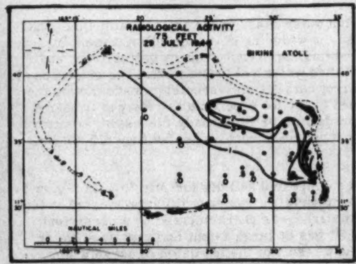

RADIOLOGICAL ACTIVITY
75 FEET
29 JULY 1946
BIKINI ATOLL
NAUTICAL MILES

Fig. 17--Radiological activity in Bikini Lagoon, 75 ft, July 29, 1946

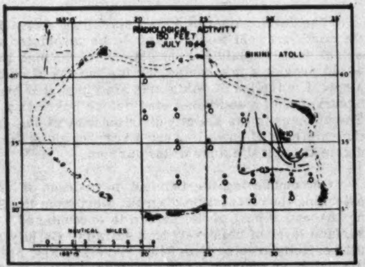

RADIOLOGICAL ACTIVITY
150 FEET
29 JULY 1946
BIKINI ATOLL
NAUTICAL MILES

Fig. 18--Radiological activity in Bikini Lagoon, 150 ft, July 29, 1946

complementary factors would appear to explain this phenomenon: First, the intrusion of ocean water through Enyu Channel which was indicated to have occurred by an analysis of the salinity distribution; second, the low values of the surface diffusion rates which would be expected to exist in a narrow band along the zone of demarcation. (Diffusion rates are discussed by VON ARX [1948]). The division of the Lagoon into two distinct systems was shown to occur in model experiments [VON ARX, 1948] in which an Enyu Current was created by a southeast wind.

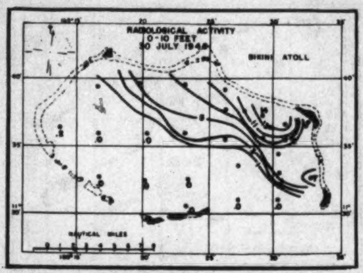


Fig. 19--Radiological activity in Bikini Lagoon, 0 to 10 ft, July 30, 1946

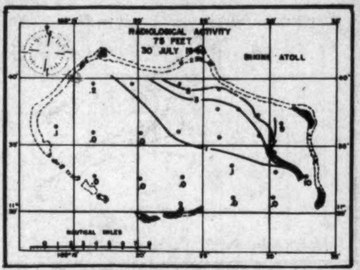


Fig. 20--Radiological activity in Bikini Lagoon, 75 ft, July 30, 1946

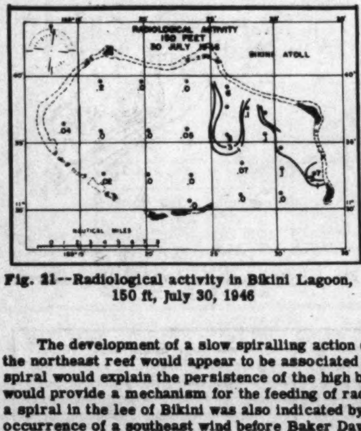


Fig. 21--Radiological activity in Bikini Lagoon, 150 ft, July 30, 1946

The region of upwelling during this period differed in a significant manner from the the norm. VON ARX [1948] reported that the normal zone of upwelling extends from the northern tip of Bikini Island to the southern tip of Enyu Island, having a width of 2400 yd opposite Rokar Island and 3300 yd behind Bikini and Enyu Islands. According to the distribution of radiological activity, the zone had widened at Bikini to more than 6000 yd with perhaps some reduction in width at Enyu. This shift of the upwelling zone may be considered a result of the Enyu Current sweeping into the southern part of the Lagoon and thus deflecting to the north the wind-driven westerly set (which was weak at this time) of the surface lagoon circulation. The model experiments referred to above also showed a similar shift of the upwelling zone.

The development of a slow spiralling action of the water mass in the lee of Bikini Island and the northeast reef would appear to be associated with the widening of the upwelling zone. Such a spiral would explain the persistence of the high but dwindling activity counts in that area, and would provide a mechanism for the feeding of radioactive water out to the west. The existence of a spiral in the lee of Bikini was also indicated by direct current measurements made during the occurrence of a southeast wind before Baker Day, and by model experiments referred to above. The changes in the salinity distribution patterns from July 28 to 30, already discussed, confirm the existence of upwelling and a current along the east and northeast reefs, but they did not indicate the spiral nature of the current.

On considering the distribution patterns of both salinity and activity for July 30 with a view to extending the circulation diagram west from the Bikini sprial, a complex situation located in the north-central part of the Lagoon is encountered. This area was characterized by a persistent surface layer of relatively high salinity. On July 28, it was of large extent and contained water with salinity greater than 34.60 $^0/_{00}$ (see Fig. 3). As a result of the intrusion of ocean water through Enyu Channel on July 29, it was displaced to the northeast and somewhat diluted (see Fig. 4). This displacement is also shown in the activity patterns for these two days (see Fig. 13 and 16). On July 30, the water of higher salinity had returned to about its position on July 28, thus indicating the presence of a westerly drift of the surface waters. This is in agreement with the westerly movement of activity shown by Figures 16 and 19 for this area. However, the persistence of the higher salinity indicates the existence of a slow eddy system in the north-central section of the Lagoon shown in Figure 22. Evidence for such a system in that area was also shown by the model experiments.

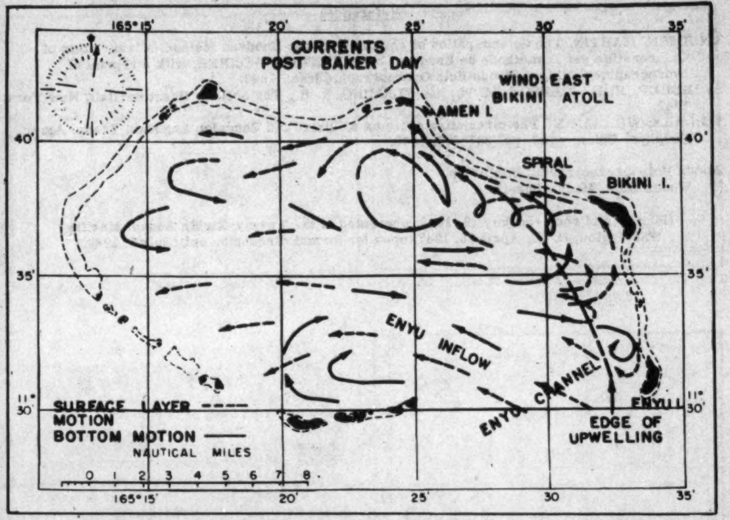


Fig. 22--General features of the currents in Bikini Lagoon as of July 30, 1946

Conclusions--The abnormal circulation of the waters of Bikini Lagoon during the several days following the underwater atomic blast has been described in some detail and with particular reference to the movement and areas of concentration of radioactive material. It is felt that this may be of value in studies of the effect of radiological contamination on the marine flora and fauna, especially the sedentary forms, at Bikini.

It has been demonstrated that the determination of radioactivity distribution in a water mass repeated at various intervals after the activity has been introduced into the system can give valuable information as to the circulation. This radioactive tracer technique in general resembles the conventional salinity method but has the considerable advantage that the activity may be put into the water at strategically selected points, either all at once, giving a zone of high concentration which will diffuse out as it moves with the water mass; or continuously, thus producing a fixed source of activity. It may be argued that the use of radioactive tracers as a general hydrographic tool would not be practical because of the danger of serious contamination of marine life in the areas to be investigated. Though all the ramifications of this question are beyond the scope of this paper, it can be pointed out that the concentrations of activity required are very small, being limited chiefly by the background count. There are certain other obvious limitations. The method would be confined to the study of relatively small areas, the size of which would depend upon the amount of radioactive material available or safely usable. Only those radioactive compounds which would not be involved in biological processes to a significant degree could be used. If, for example, radioactive phosphorus as a soluble phosphate were to be used in quantities suitable for use as a radioactive tracer of a water circulation, it would be at levels of concentration comparable to the normal range of phosphorus in the sea [0.0 to 3.0 microgram atoms per liter, SVERDRUP, JOHNSON, and FLEMING, 1942, p. 241] and would therefore be subject to removal from solution by biological activity.

Acknowledgment--The radiological data presented here were made available to the author through the kindness of K. G. Scott and Gifford Ewing following release by the The Commander, Joint Task Force One (Operation Crossroads).

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SUBMARINE GEOLOGY AND TOPOGRAPHY IN THE NORTHERN MARSHALLS

K. O. Emery, J. I. Tracey, Jr., and H. S. Ladd

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Abstract--The atomic bomb tests at Bikini in 1946 provided an opportunity to study the characteristics of atolls using modern surveying techniques. The work has shown that many of the important features, both above and below sea level, are definitely related to the direction of the prevailing winds, waves, and currents.

Beyond the windward (north and east) reefs of Bikini, the steep outer slope is broken in most places by a terrace at ten fathoms. The margin of the windward reef is a *Lithothamnion* ridge, cut by strong grooves or surge channels; large islands are developed on these reefs. Lee reefs have nearly vertical outer slopes near the surface; their margins are smooth and are adapted to light surf; occasional storms have eroded large slump areas; and islands are small and few. Passes are largely confined to the southern reefs.

The lagoons studied are 25 to 35 fathoms deep and are bordered by a ten-fathom terrace. The floors are covered with living *Halimeda* and algal debris surrounded by a belt of foraminiferal and coral sand. Steep coral knolls, some rising nearly to sea level, are scattered in the lagoons.

Many flat-topped seamounts are present in the area. The 14 that were well surveyed rise from 2500 fathoms to depths between 470 and 850 fathoms.

Introduction--In connection with the atomic bomb tests at Bikini Atoll, studies were made of the outer slopes of the atoll, of the reef and islands, and of the enclosed lagoon. For comparison, the nearby atolls, Eniwetok, Rongelap, Rongerik, and Ailinginae also were investigated. All of the atolls are at the northern end of the Marshall Group, a region in which the wind, the swell, and the ocean current generally move in a westerly to southwesterly direction. Even the most casual examination of the charts of the Marshall Group indicates a prevalent orientation of various features of the atolls in relation to exposure, or to direction of the prevailing winds. Other similar relationships were observed by studies of aerial photographs and by field work in the area.

Outer slopes--Soundings taken during the survey show that the atolls rise from depths of about 2500 fathoms on slopes which are steepest near the surface of the ocean. The top of the outer slope bordering the reef on the leeward side of Bikini and the other atolls is nearly vertical, but the reef on the windward side is partly fringed by a ten-fathom terrace. This terrace is widest within the broad re-entrants between reef projections. The exceptionally steep slopes off the leeward reef may indicate an unstable seaward reef growth into the generally quiet water in the lee of the atoll. At times of storms, particularly storms from the southwest, the edge of this reef may be broken away because of its instability, but the windward reef is not much affected because it is built directly against heavy swells which probably are able to break away unstable growths before they become very large. Examination of Figure 1 shows that slump areas, in which the outer reef edge has broken away, are present on the leeward sides of three of the five atolls and on the windward side of none.

The outer slopes are also characterized by spurs which extend downward beyond projecting points of the reefs. Northwest of Bikini and connected by only a narrow neck is a broad, flat seamount whose surface lies between depths of 700 and 850 fathoms. A large current eddy west of Bikini [BARNES, BUMPUS, and LYMAN, 1948] probably owes its presence to this seamount. A number of additional seamounts are present in the northern Marshalls. Fourteen of them are considered well surveyed, and their shallowest depths range between 470 and 850 fathoms, averaging 690 fathoms. These seamounts are presumed to be volcanoes which have been bevelled by wave erosion at some period during the past.

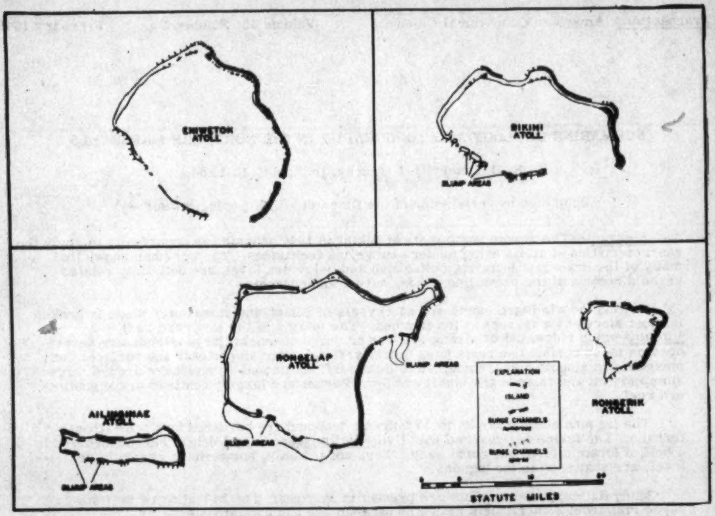

Fig. 1--Outline maps of five atolls in the northern Marshall Islands showing distribution of islands, surge channels, and slump areas

Bottom samples from points shallower than 250 fathoms show that the upper part of the outer slopes is composed chiefly of blocks of reef rock (coral and Lithothamnion, a calcareous red alga) in a matrix of loose segments of Halimeda (a calcareous green alga) and Foraminifera. This material grades to fine calcareous sand at about 600 fathoms. Samples from the top of the seamount adjacent to Bikini Atoll consist almost entirely of Globigerina sand. Sampling by earlier expeditions shows that the deep-sea floor is covered by Globigerina ooze grading laterally to red clay.

Reef and islands--The subaerial part of the atolls is mainly a wide reef flat on which the islands are superimposed. The reef flat consists mostly of algal and coral limestone, large parts of which are veneered with Foraminifera. The islands are composed of sandy debris overlying reef limestone. Living Lithothamnion with subordinate amounts of corals form a low ridge at the seaward edge of the reef. Cutting through this Lithothamnion ridge are numerous surge channels, usually about five ft wide, 15 ft deep, and 50 ft long [MUNK and SARGENT, 1948]. The main reefs are also penetrated by passes of varying depth and width but mostly large enough to allow the passage of ships.

A summary of the relationship of islands, surge channels, and passes to wind direction is given in Figures 1 and 2. The diagram for wind in Figure 2 is based on data accumulated over a period of 19 years at Ujelang Atoll. The length of each radial spoke indicates the annual percentage of time that the wind blows from that octant.

The three other diagrams of Figure 2 show what is called the azimuth of the islands, surge channels, and passes, that is, the direction in which each of these features is concentrated. The data for these diagrams were compiled from measurements of all five of the atolls shown in Figure 1. Each spoke in the diagram for islands represents conditions over a 15° arc. The direction of the spoke is at right angles to the trend of the reef in the 15° of arc. The length of each spoke is a measure of the number of statute miles of islands in the segment, the island length being measured parallel to the reef front. The same system is followed in the diagrams showing the distribution of passes and of reefs with surge channels.

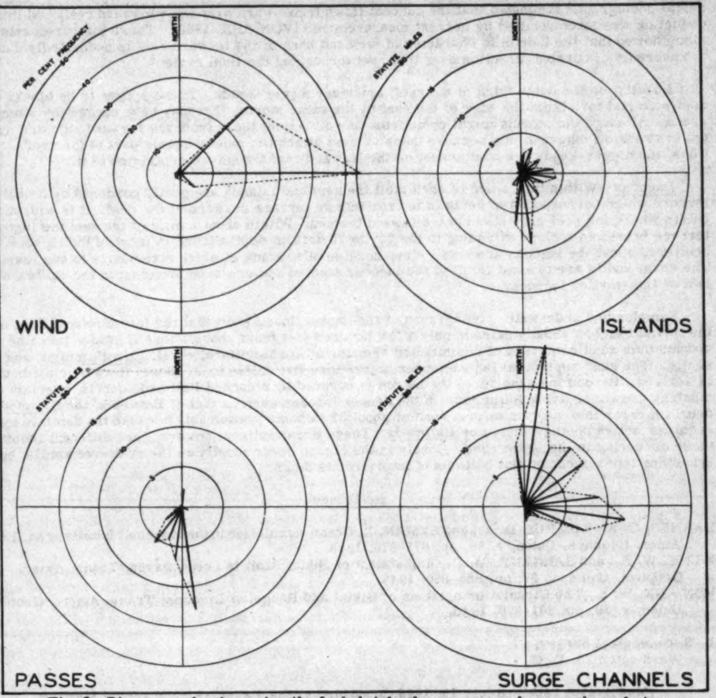

Fig. 2--Diagrams showing azimuth of wind, islands, passes, and surge channels in parts of northern Marshall Islands

The diagram showing islands exhibits a marked development of islands in the northeast and southeast quadrants, which are directly or nearly upwind. The one for passes shows that large reef openings occur most commonly on the south side of the atolls, neither directly upwind nor downwind. The surge-channel distribution bears the closest relationship to the wind diagram, although the two are not identical in pattern, there being a marked abundance of surge channels on the north side. Some of the irregularities of the diagrams are due to the refraction of swell, and some probably are dependent on the general shapes of the atolls. The relationships that are present are in accordance with the suggestion that growth of Lithothamnion is most rapid in the zone of violent surf on the swellward side, thereby producing surge channels on that side. Similarly, where growth is most rapid, comminution is most rapid, producing debris which is carried across the reef and deposited as islands, which also are approximately on the swellward side. Slow growth of Lithothamnion on the south leeward side may result in failure to close up reef gaps, leaving them as passes.

Relationship to wind and swell direction is not confined to large reef features. Scattered along the center of the reef, particularly on the windward side, are many small discontinuous sand bars. Nearly all of these bars have curved ends, which on the windward reef point toward the lagoon. Similarly, the sand spits at the ends of the windward islands also are curved and point toward the lagoon. On the leeward side also the reef has a few sand bars, but the tips of these show a less definite preferred direction. Prior to arrival at Bikini Atoll, study of the sand bars shown on

aerial photographs suggested that the current flows lagoonward over the windward reef, and this deduction was later verified by current measurements [VON ARX, 1948]. These measurements also showed that the indefinite character of the sand bars of the leeward reef is undoubtedly due to reversals of current direction over that reef throughout the tidal cycle.

Locally, on the outer third of the reef, are many nigger-heads. These appear to be blocks of reef material torn from the edge of the reef by the same storms that may have caused the slump areas. Although the storms might come from any direction, those from the leeward side are most apt to break off nigger-heads because those storms attack the most unstable part of the reef. Thus, the nigger-heads are commonest on the leeward reef though not restricted to it.

Lagoons--Within the lagoon of each atoll the reef and islands are partly bordered by a shallow terrace which corresponds in depth to the ten-fathom terrace seaward of the reef. It is widest at points where the reef projects outward toward the sea. Within about a mile of the reef the lagoon terrace breaks in a slope extending to the 25- to 35-fathom depths found in most of the lagoons. Scattered about the lagoons are small steep coral knolls, some of which rise nearly to sea level. The coral knolls are present in all of the lagoons studied and are most abundant in the eastward half of the smaller lagoons.

Samples and underwater photographs of the lagoon floors show that the foraminiferal sand of the island beaches usually extends only a few hundred feet from shore where it grades into fine and medium sand composed of comminuted remains of Foraminifera, coral, Lithothamnion, and shells. The sand zone in all lagoons extends less than five miles from shore, from which it probably is derived. Beyond the sand zone, the lagoon is covered by bleached Halimeda debris, overlain by a patchy growth of living Halimeda. In the deeper lagoons such as that of Eniwetok, the Halimeda debris merges into a foraminiferal sand at about 32 fathoms presumably because the depth is too great for active photosynthesis by Halimeda. These Foraminifera, however, are different from those occurring in the shore zone. Corals in the lagoon occur mostly on the scattered knolls, but branching types occur on flat bottoms of intermediate depth.

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DIFFUSION IN BIKINI LAGOON

W. H. Munk, G. C. Ewing, and R. R. Revelle

(Contribution from the Scripps Institution of Oceanography, New Series, No. 403)

Abstract--During the preliminary survey at Bikini, the state of turbulence in the lagoon was determined from three types of measurements: simultaneous measurements of surface current and wind speed, measurements of diurnal temperature fluctuations at various depths, and measurements of the rate of mixing of the oxygen-rich reef water with the body of the lagoon water. These measurements lead to reasonably consistent values for the coefficient of vertical diffusion. The coefficient of horizontal diffusion was estimated on the basis of past observations and of measurements of the lateral spread of dye markers. Its estimated value compares favorably to a value computed from the lateral spread of radioactive material deposited during the underwater atom-bomb burst.

Introduction--Two factors were principally responsible for reducing the intensity of radioactivity of the lagoon water after each bomb burst: radioactive decay and diffusion. Diffusion studies were undertaken in the spring of 1946 to aid in a prediction of how soon after each burst the lagoon might be safe to enter.

By analogy with the process of diffusion due to random molecular motion it is customary to define a coefficient of eddy diffusion A by the equation [SVERDRUP, JOHNSON, and FLEMING, 1946, pp. 69, 92-93].

$$M = -A\,\partial S/\partial n \qquad (1)$$

where M is the amount of substance which per unit time diffuses through a unit surface area, and $\partial S/\partial n$ the concentration gradient along a line normal to that surface. The coefficient A is usually more than a million times the corresponding molecular coefficient. Its value depends not only on wind speed, current shear, density gradient, and the scale of the phenomenon, but also on the diffusion direction. According to previous measurements, the coefficient of vertical eddy diffusion. A_v varies from one to 320 cm^2/sec; that of horizontal eddy diffusion A_h from 2×10^6 to 4×10^8 cm^2/sec [SVERDRUP, JOHNSON, and FLEMING, 1946, pp. 483-486].

Too little is known about diffusion to make an estimate of the numerical values of the coefficient pertaining to Bikini Lagoon. Preliminary work at Bikini was therefore directed toward determining these values. Once they were known the rate of spread and dilution of any initial contamination could be computed.

The original plan provided for an experiment, for which radioactive materials were to be flown from the United States and dropped into the lagoon. This experiment was cancelled, but fortunately existing natural conditions provided several excellent methods for estimating the values of the diffusion coefficients.

Part I--Preliminary survey, March to April 1946

Surface current and wind speed--For winds exceeding 6.5 m/sec (13 knots) the stress applied by the wind on a unit surface area equals [SVERDRUP, JOHNSON, and FLEMING, 1946, p. 490]

$$2.6 \times 10^{-3} \rho U^2 \qquad (2)$$

where ρ is the density of air, U the wind speed at about ten m above the water. Assume the wind stress to be balanced by the shearing stress in the water of magnitude

$$A'_v\, \partial u/\partial z_x \qquad (3)$$

where u is the horizontal current at a depth z (z = 0 at surface, z = h at bottom), and A'_v is the coefficient of vertical eddy viscosity, assumed constant from top to bottom. As a very rough approximation let

$$u = u_0 (1 - 2z/h) \qquad \text{(4)}$$

so that the net volume transport $\int_0^h u\,dz$ between surface and bottom equals zero. The vertical current gradient, and hence the shearing stress, is then independent of depth. Combining (2), (3), and (4) and setting $\rho = 1.25 \times 10^{-3}$ g/m^3, h = 5000 cm (165 ft), gives

$$A'_v = 2.6 \times 10^{-3} \rho \; U^2 h/2u_0 = 8.15 \times 10^{-3} \; U^2/u_0 \qquad \text{(5)}$$

In Figure 1 u_0 has been plotted against U for various values of A'_v. Comparison with observations, also entered in Figure 1, indicates a value for A'_v between 200 and 300 cm^2/sec.

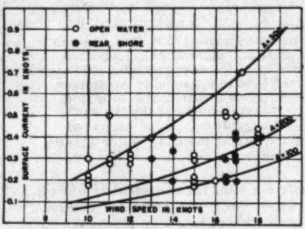

Fig. 1--Circles represent simultaneous observations of wind speed and surface current; lines give the theoretical relationships according to (5) for various values of the eddy viscosity coefficient

The waters in Bikini Lagoon are so thoroughly mixed that the temperature difference between surface and bottom rarely exceeds 0.5°F [FORD, 1949]. Consequently one may expect the numerical value of the diffusion coefficient for radioactive material approximately to equal the eddy viscosity coefficient [SVERDRUP, JOHNSON, and FLEMING, 1946, p. 477].

Diurnal temperature fluctuations--Solar radiation induces a slight diurnal variation in temperature within a very thin surface layer where practically all heat is absorbed. Let the temperature deviation from the mean surface temperature be given by the equation

$$(\Delta\phi)_0 = \theta \cos (2\pi/T)t \qquad \text{(6)}$$

where θ is the amplitude of the temperature cycle at the surface, and T is the period of the cycle, here 24 hr. As a result of vertical mixing subsurface layers partake in the diurnal cycle according to the equation [SVERDRUP, JOHNSON, and FLEMING, 1946, pp. 135-136]

$$(\Delta\phi)_z = \theta e^{-rz} \cos [(2\pi/T)\, t - rz] \qquad \text{(7)}$$

where $(\Delta\phi)_z$ is the temperature deviation at the depth z from the mean temperature at that depth. and r is related to the coefficient of vertical eddy conductivity A''_v by the equation

$$A''_v = \pi/T\, r^2 \qquad \text{(8)}$$

The effect of horizontal diffusion, and of horizontal and vertical advection, is neglected in (7).

The amplitude of oscillation decreases exponentially with depth, and the phase lag relative to the surface cycle increases linearly with depth. The parameter r, and hence the eddy conductivity A''_v, can be computed from either the measured amplitudes of oscillation, or the measured phase lag. The numerical value for the eddy diffusivity should be approximately that of the eddy conductivity.

Temperatures were measured at the surface and at three depths by means of reversing thermometers and bathythermographs. These measurements were made once every two hours for more than 24 hours at two anchor stations. Coefficients of A''_v were computed from the amplitude ratios, and the measured phase lags used as a check.

For the eastern station, located about three miles southwest of Bikini Island, these measurements gave values of A''_v between 260 and 320 cm^2/sec (see Fig. 2). For the western station, about seven mi from the western reef, this method gave values of A''_v of about 2000 cm^2/sec (see Fig. 3). This unreasonably large value was ascribed to vertical advection due to sinking of water in the western third of the lagoon, a feature which would tend to increase the amplitude of subsurface temperature fluctuations. Calculations gave a sinking speed of about two mi/hr, a value consistent with other considerations. The fact that A''_v at the eastern station was not unreasonably small would indicate that the rising of water due to upwelling is confined to a narrow zone adjacent to the reef.

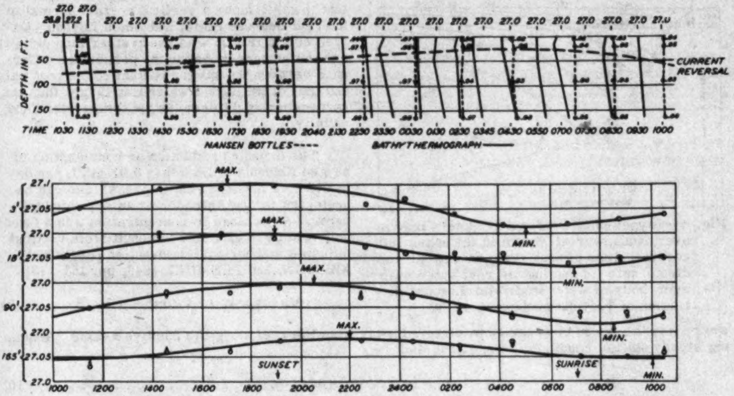

Fig. 2--Diurnal variations in temperature at various depths in the eastern portion of Bikini Lagoon; upper portion of figure gives vertical sections of temperature from measurements by means of bathythermographs and Nansen bottles; from these the variations in temperature at four fixed depths were computed and plotted in the lower portion of the figure

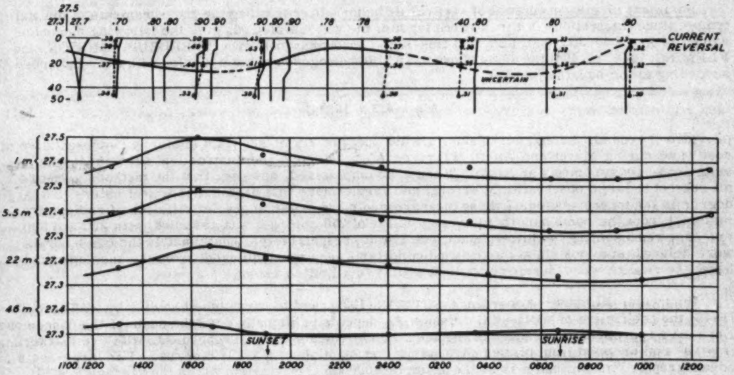

Fig. 3--Diurnal variations in temperature at various depths in the western portion of Bikini Lagoon

Diffusion of reef water--Trade-wind waves drive water over the northern and eastern reef, thereby causing a continuous current from the ocean into the lagoon [MUNK and SARGENT, 1948]. At noon, especially during low tide, the water is appreciably warmed as it flows over the wide reef; it also increases in salinity, and it becomes saturated with oxygen. Upon flowing into the lagoon this reef water can be recognized as a distinct water type. The rate of mixing of the reef water with the main body of the lagoon water provides a means of estimating the coefficient of diffusion.

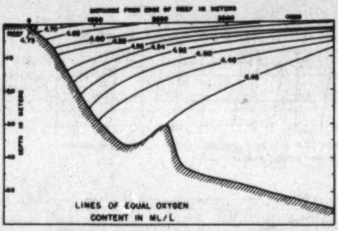

Fig. 4--Oxygen-rich reef water enters lagoon over shallow reef shown in the upper left corner; lines of equal oxygen content indicate rate of mixing of reef water with main body of water in Bikini Lagoon; direction of vertical section, S 40° W

Figure 4 shows lines of equal oxygen content in ml/L along a vertical section normal to the reef between Bikini and Amen Islands. Oxygen concentration was used rather than salinity or temperature, because the percentage difference between the oxygen content of the reef water and that of the lagoon water was larger than the corresponding differences for temperature and salinity.

The organic production or consumption of oxygen amounts to less than 0.01 ml/L per day [SARGENT and AUSTIN, in press], and can be neglected without introducing an appreciable error. Any change in concentration s in a fixed unit volume is assumed to result from vertical diffusion and horizontal advection [SVERDRUP, JOHNSON, and FLEMING, 1946, pp. 153-163].

$$\partial s/\partial t = A_v \, \partial^2 s/\partial z^2 - u \, \partial s/\partial x \quad \ldots (9)$$

where u is the speed of water flow, directed away from the reef along the positive x-axis. Assuming steady station conditions, $\partial s/\partial t = 0$, and

$$A_v = (u \, \partial s/\partial x)/(\partial^2 s/\partial z^2) \quad \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

The mean value for u was determined from measurements with the Von Arx current meter [VON ARX, 1948] and amounted to 20 cm/sec (0.4 knots). Values of $\partial s/\partial x$ and $\partial^2 s/\partial z^2$ were determined graphically from Figure 4. The coefficient of vertical diffusion was then computed according to (10) for various positions in the vertical section. Values of A_v increase with distance from the surface and decrease with distance from the reef. The average value for A_v is 260 cm^2/sec.

Summary of measurements of vertical diffusion--Disregarding the measurements of diurnal temperature fluctuations in the western lagoon, the various methods give the following numerical values of A_v: 200-300, 260, 320, 260 cm^2/sec. According to Ekman [SVERDRUP, JOHNSON, and FLEMING, 1946, p. 494] the eddy viscosity A'_v in homogeneous water varies with the wind speed U according to the equation

$$A'_v = 4.3 \times 10^{-4} U^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

provided U exceeds 6.5 m/sec. Taking a wind speed of 7.5 m/sec (14.5 knots) as representative of conditions during March and April, (11) gives $A'_v = 240 \ cm^2/sec$, in excellent agreement with results from measurements at Bikini. It must be emphasized, however, that the methods used are all subject to large observational errors, and furthermore that personal judgment enters to a large degree in the interpretation of these measurements. In order to predict diffusion of radioactive material from the bomb bursts an average value of 250 cm^2/sec was assumed, with 200 and 300 cm^2/sec representing the lower, and upper limits, respectively. Unfortunately the bomb bursts were delayed, and took place during wind conditions very much different from the ones assumed here; the results were therefore applicable only to a limited extent.

Horizontal diffusion--According to SUTTON [1932], and to unpublished studies by SVERDRUP [1946] the coefficient of horizontal diffusion A_h depends principally upon the scale of the phenomenon. Let r be a representative radius of the area under consideration. Experiments with dye markers ($r = 10^3$ cm) dropped from planes gave values for A_h of about $5 \times 10^2 \ cm^2/sec$. For large-scale oceanographic phenomenon r is of the order of 1000 km (10^8 cm) and A_h on the average $5 \times 10^7 \ cm^2/sec$. For these two extreme examples the value of r varies by a factor of 1:100,000, whereas the ratio A_h/r varies only from 0.2 to 0.5. As a representative value for Bikini the ratio $A_h/r = 0.4$ was chosen.

Part II--Diffusion of radioactive materials deposited by the atomic bomb

Observations--The following discussion refers only to the underwater burst [Baker]. The concentration of radioactivity is given in arbitrary radiation units (aru), which have been corrected for radioactive decay on the basis of laboratory experiments with sea water. The analysis is restricted to the first three days after the burst (from B + 1 to B + 3), because following this period a shift in wind direction greatly complicated the picture. Changes in the distribution of radioactivity should be due only to processes of diffusion and advection, except for the possibility of re-activation of water passing over radioactive wreckage, or over contaminated portions of the lagoon bottom.

Table 1--Number of measurements of radioactivity

Depth	Time			Total
	B + 1	B + 2	B + 3	
ft				
0	41	42	42	125
10	24	29	36	89
75	15	30	35	80
150	12	21	31	64
Total	92	122	144	358

Table 1 shows the number of measurements at various depths in a region of about six-mi radius surrounding the target area.

Water samples were collected by the Oceanographic Division of the Radiological Safety Section of Joint Task Force One in addition to their other duties. The samples were analyzed by K. G. Scott of that Section and the radioactivity determined to at least three significant figures. These measurements are more closely spaced and much more accurate than any equivalent set of measurements taken in the past; they constitute the best material that has been available for the study of diffusion in the sea.

As is so often the case when quality and quantity of measurements are improved, the phenomenon under consideration reveals itself to be more complex than has been previously assumed. The spottiness of the distribution is striking; on B + 2, for example, a concentration of 60 aru was measured within 1500 ft of three observations of about two aru. Since many, if not most, small regions of high radioactivity must have escaped observations, the analysis must be confined to the main features.

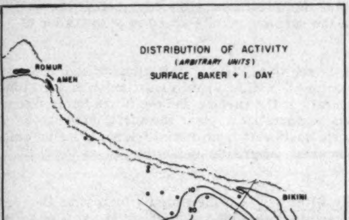

Fig. 5--Distribution of radioactivity in surface waters of Bikini Lagoon; Baker + 1 day

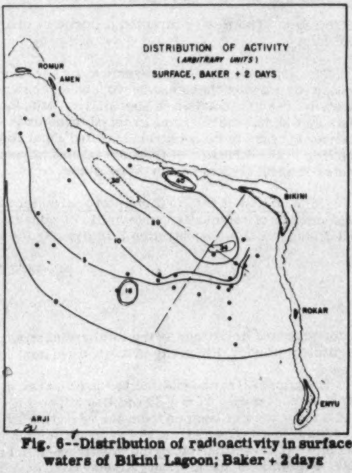

Fig. 6--Distribution of radioactivity in surface waters of Bikini Lagoon; Baker + 2 days

Qualitative description of the diffusion of contaminated water--In examining the distribution shown in Figures 5 to 7, one should hold in mind that they are based on measurements extending over many hours, rather than on simultaneous measurements.

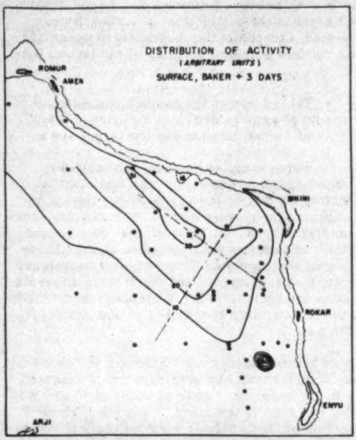

Fig. 7--Distribution of radioactivity in surface waters of Bikini Lagoon; Baker + 3 days

The surface distribution on B + 1 (see Fig. 5) shows one well-defined maximum southwest of Bikini Island; another maximum south of Bikini Island. By the second day (see Fig. 6) the concentration is elongated along a northwest-southeast axis, and the center of concentration has moved several miles to the northwest. The contamination has spread at right angles to the direction of drift. A number of secondary high-concentration areas are present which were not apparent from the surface distribution on the first day. Among these, the area with a maximum of 41 aru probably resulted from upwelling against the reef. The surface distribution on the third day (see Fig. 7) has drifted further towards the northwest.

The most prominent feature the of the changes in surface distribution of radioactivity is therefore a lateral spread of the contamination, superimposed upon a slow drift. The direction of drift is toward the northwest, in the direction the wind was blowing. The drift speed is about 0.1 knots.

The highest concentrations are usually found at depths of about 75 ft, sometimes even deeper. Unfortunately measurements at subsurface depths are more scarce, and not even the main features of the distribution are well established. The flow is directed opposite to that at the surface, and its speed is of the order of 0.03 knots.

The general pattern of movement, or advection, is shown in Figure 8. Regions of high concentration for various times and at various depths are entered, and the probable direction of drift indicated. The presentation is speculative. Measurements at the surface and ten ft are fairly consistent, and will therefore be grouped together in our computations. Near the surface the radioactivity appears to be most concentrated about four km southwest from Bikini Island, along an axis pointing in the direction of flow and labeled advection axis. At greater depth the radioactivity is centered about ten km southwest of Bikini.

Computation of the coefficient of horizontal eddy diffusivity--At the time $t = 0$, assume the total amount of radioactive material to be concentrated along the line $x = 0$. Then at any time t and distance x the concentration S is given by the normal distribution equation [McEWEN. 1946].

$$S = S_0 e^{-(x/\sigma)^2/2} / \sigma\sqrt{2\pi} \quad \ldots\ldots (12)$$

where

$$\sigma = \sqrt{2A_h t} \quad \ldots\ldots (13)$$

is the standard deviation, S_0 the total radioactivity per unit length of line, and A_h the kinematic coefficient of eddy diffusivity in the x-direction. The coefficient A_h is assumed constant.

Equation (12) has been fitted to the observed distribution of radioactivity at the surface and at ten ft depth, for B + 1, B + 2, and B + 3 (see Fig. 9). Each point represents the mean distance x of a radioactivity contour from the advection axis. The positive x-axis extends in a southwesterly direction, that is, away from the reef. Diffusion toward the northeast is inhibited by the reef; therefore observations along the positive x-axis have been given more weight in fitting the curves than observations along the negative x-axis.

According to Figure 9, the measured concentration near the center always exceeds the concentration maximum given by (12), indicating perhaps that the assumption of constant A_h may not be valid.

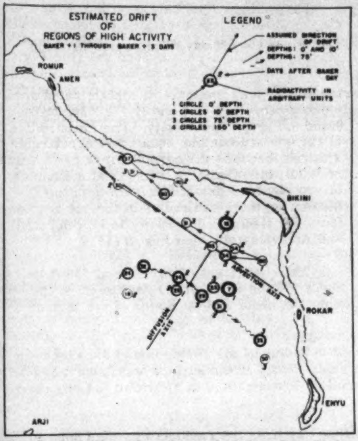
ESTIMATED DRIFT
OF
REGIONS OF HIGH ACTIVITY
BAKER + 1 THROUGH BAKER + 3 DAYS
LEGEND
ASSUMED DIRECTION OF DRIFT
DEPTHS: 0' AND 10'
DEPTHS: 75'
DAYS AFTER BAKER DAY
RADIOACTIVITY IN ARBITRARY UNITS
1 CIRCLE 0' DEPTH
2 CIRCLES 10' DEPTH
3 CIRCLES 75' DEPTH
4 CIRCLES 150' DEPTH
ROMUR
AMEN
BIKINI
ADVECTION AXIS
DIFFUSION AXIS
ROKAR
ENYU
ARJI

Fig. 8--Location of regions of high radioactivity during B + 1 through B + 3, and their estimated drift

The total amount of radioactive material in the surface layers is proportional to S_0, the area under the curve through the points. Numerical values of S_0 are listed in the second column of Table 2. For the first two days S_0 remains approximately constant. For the third day it is one-fourth larger, probably due to upwelling of material from greater depth. All observations for the third day were consequently multiplied by a factor of 0.80 to make the distribution during the three days comparable. The third column in Table 2 lists the standard deviations of the curves in Figure 9.

Let σ_1, and σ_2 designate values of the standard deviation at t_1 and t_2, respectively; according to (13)

$$A_h = (\sigma_2^2 - \sigma_1^2)/2\,(t_2 - t_1) \quad \ldots\ldots \quad (14)$$

where A_h represents the mean value of the coefficient between times t_1 and t_2.

Values of A_h in Table 3 have been computed according to (14) from the observed changes in distribution between various times, where it has been assumed that the distribution on B + 1 can be fitted by a normal curve. It is of some interest to compute the time interval which would have to elapse for an initial distribution along a line x = 0 to assume the distribution found at B + 1. According to (13) this time interval must equal

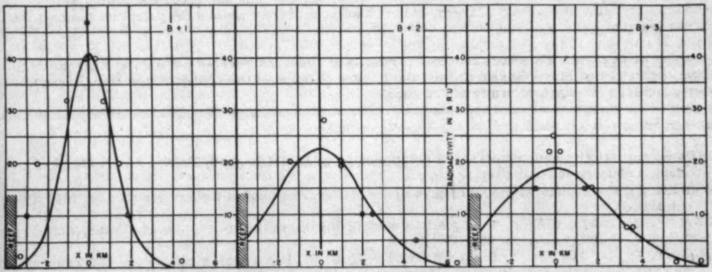

Fig. 9--Observed and computed distribution in radioactivity

Table 2--Quantity of radioactive material in the surface layers, and standard deviation of its distribution about advection axis

Time	S_0	σ
days	aru	cm
B + 1	1.29×10^7	1.15×10^5
B + 2	1.23×10^7	2.10×10^5
B + 3	1.57×10^7	2.52×10^5

Table 3--Values of the coefficient of horizontal eddy diffusivity

t_1	t_2	A_h
day	day	cm^2/sec
B + 1	B + 2	1.8×10^5
B + 2	B + 3	1.2×10^5
B + 1	B + 3	1.5×10^5

$$t = \sigma^2/2A_h$$

Setting $\sigma = 1.15 \times 10^5$ cm, and $A_h = 1.5 \times 10^5$ cm^2/sec, gives t = 1/2 day. This value is of the correct order of magnitude.

Evaluation of A_h at subsurface depths was carried out for only one case, a contaminated area at a depth of 150 ft (see Table 4), which diffused noticeably between B + 1 and B + 2. For these two days the concentrations near the center were 7.0 and 6.5 aru, respectively. The mean radius of the one aru contour equals two standard deviations, because the normal curve has a value of 1/7 of the maximum ordinate at a distance of two standard deviations from the center. Measuring the mean radius of the one aru contour, the standard deviation can be computed, and A_h evaluated according to (14).

Table 4--Computation of A_h at 150 ft depth

Time	Mean radius of 1 aru contour	σ	A_h
day	cm	cm	cm^2/sec
B + 1	1.64×10^5	0.82×10^5	0.5×10^5
B + 2	2.50×10^5	1.25×10^5	

The coefficient of diffusion at 150 ft is about 1/3 the value of the coefficient at the surface. It may be significant that the drift at that depth has about 1/3 the speed of the surface drift.

Summary of Part II--A representative value for the radius of the contaminated area between B + 1 and B + 3 is 3 km or 3×10^5 cm. The mean value for A_h at the surface was found to be 1.5×10^5 cm^2/sec. This gives $A_h/r = 0.5$ cm/sec, in excellent agreement with a ratio of 0.4 proposed prior to the burst.

A determination of the coefficient of vertical diffusivity from the radioactivity data does not appear feasible, due to difficulties of separating the vertical diffusion from vertical advection (upwelling against the reef), and due to the extreme patchiness in the distribution of radioactive material. This patchiness, although it prevents more refined methods of analysis, is in itself a finding of considerable interest. It indicates not only patchiness in the initial distribution of radioactivity as it was deposited by the atomic bomb, but also that the turbulent eddies which spread the contamination over a larger area did not appreciably reduce the patchiness during the first three days.

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THE DISSIPATION OF WAVE ENERGY BY BOTTOM FRICTION

J. A. Putnam and J. W. Johnson

Abstract--A theory is developed for the loss in wave energy as a result of friction by the oscillating motion of waves at the sea bottom. This loss in energy is reflected as a reduction in the wave height as the waves move shoreward. It is shown by numerical examples that this reduction may amount to as much as 30 per cent on very flat beaches for wave periods commonly occurring in the ocean.

Introduction--After leaving a generating area, oscillatory waves run freely in a region in which the wave-generating forces have ceased to operate, losing energy by friction as they proceed. In nature, wave heights are probably reduced by an increase in wave length as the waves move away from the generating area. In any event, internal friction converts mechanical energy into heat owing to the fact that velocity gradients exist due to the wave motion and, in view of the viscosity of the water, fluid elements are distorted.

This problem has been treated previously [LAMB, 1932, p. 623; HOUGH, 1896], where it was shown that the time of travel necessary for a wave to be reduced in amplitude in the ratio 1/e is

$$t_r = L^2/8\nu\pi^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where L is the wave length and ν is the kinematic viscosity of the fluid. Evidently for fluids having small viscosities, such as water, the velocity of the wave and the relationship between depth, length, and period are unaltered by internal friction. The theory upon which (1) is based starts from the assumption of a sinusoidal wave form, but the result appears to indicate a very slow rate of damping of all waves in deep water, which is in accord with limited observations in nature.

Following or opposing winds at the sea surface are considered here to act in the nature of generating agencies, adding or withdrawing energy from the waves with but little dissipation of the energy. These phenomena have been described elsewhere [SVERDRUP and MUNK, 1947].

In considering shallow-water waves, it can be demonstrated readily, both theoretically and experimentally, that the orbital velocities are finite at the bottom and actually approach the theoretical values at a small distance from a smooth bottom. A boundary layer in which mechanical energy is dissipated through distortion of fluid elements must, therefore, exist at the bottom. If the sea bottom consists of a permeable bed of sand, pressure variations due to wave motion will induce currents in the permeable layer and these currents in turn will dissipate some of the mechanical energy of the wave.

It is the purpose of this paper to investigate the effects of bottom friction on the dissipation of wave energy. The effect of flow within a permeable sea bottom is discussed elsewhere [PUTNAM, in preparation].

Friction characteristics of a sea bottom--In the vicinity of the bottom the water particles oscillate with a motion which is theoretically sinusoidal but which is actually a rapid forward motion under the wave crest and a slower backward motion under the trough. Because of the oscillatory motion of the water, the boundary layer is probably thinner than the height of the roughness and the bottom might be expected to behave as a hydraulically rough surface in the sense that the friction coefficient depends only on the roughness and not directly upon the viscosity of the water. The effective roughness of sandy bottoms is probably determined by the ripple size rather than the size of the sand grains. However, the ripple size would appear to be determined by the size and sorting characteristics of the sand, in addition to the height and period of the wave and the depth of water.

In connection with the development of ripples of a sandy bottom by means of wave action, experiments by BAGNOLD [1947] are of importance. These experiments give quantitative data on (1) the size and character of the sand ripples made by waves, (2) on the drag to which these ripples give rise, and (3) on the minimum oscillating water motion required to disturb the sand in the first instance. The procedure used in the tests consisted of oscillating the bottom harmonically through still water instead of the usual procedure of generating surface waves which moved over a fixed bed of sand. For the tests on ripple development, sand was placed in an oscillating cradle; however, for measurement of drag forces and friction factor, an oscillating plate with an idealized ripple shape molded on to each side was used. The pitch height ratio of these idealized ripples was 6.7/1 and the ripple trough sections consisted of circular arcs meeting to form sharp crests at an angle of 120°. Two plates were used, on one of which the ripple pitch, p, was 10 cm and on the other twice that size.

These investigations on drag are of interest in the present paper in that information is given on the friction coefficient for a surface roughened by sand ripples, as might be found on the ocean bottom. Bagnold found that when the ratio of the half-amplitude of horizontal displacement, R, at the bottom to the spacing of the ripples p was less than unity, the value of the friction factor k (see Appendix 1) was a constant and was equal to 0.08. When the ratio R/p was greater than unity (as would probably be the case in the ocean) then the friction factor was given by the relationship

$$R = 0.072\,(R/p)^{-0.75} \ldots\ldots\ldots\ldots (2)$$

This equation has been used in this paper for arriving at the general magnitude of k which is used in estimating the reduction in wave height due to friction. Thus, if a 12-sec period wave, with a height of four ft, is moving in relatively shallow water (say $d/L_0 = 0.03$) a consideration of basic wave theory [O'BRIEN and OTHERS, 1942] shows that the ratio of full amplitude at the bottom to the wave height is approximately $2R/h = 2.25$, from which R, the half amplitude, for a wave four ft high, is equal to 4.5 ft. With this value of R and assuming that the pitch of the ripples is about five inches, as appears reasonable from the condition illustrated in Figure 1, solution of (2) gives a value of the friction factor k of approximately 0.01. As indicated below, this value for the friction factor has been used in the computations for estimating the effect of bottom friction on the dissipation of wave energy and consequently the change of wave height. The ripples shown in Figure 1 were photographed on a beach that had just been uncovered due to the falling tide and were protected from subsequent breaker action by an outer bar.

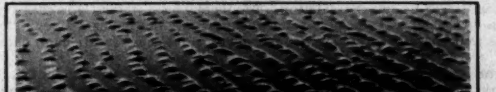


Fig. 1--Ripple marks exposed at low tide at Copalis Beach, Washington; ripple pitch is 4-5 inches; (a) side view, (b) front view

Analysis--In order to estimate the order of magnitude of the energy loss due to bottom friction, the following analysis can be used. The basic assumptions upon which the analysis is based are the following:

(1) The oscillatory motion at the bottom is sinusoidal and corresponds to the wave theory based on small amplitudes.

(2) The friction coefficient does not vary with velocity and is approximately independent of water depth. This assumption amounts to choosing an average friction factor for the entire region over which the sea bottom affects the wave motion.

(3) Perpendicular flow at the bottom, resulting from percolation in the bottom material, is negligibly small.

(4) The sea bottom is a plane surface of constant slope upward to the breaker line.

In accordance with elementary concepts of fluid friction, the tangential stress on unit area at any instant is given by

$$\tau = k\rho U_h^2 \quad \ldots\ldots (3)$$

The instantaneous rate at which energy is dissipated per unit area is

$$\tau U_h = k \rho U_h^3 \quad \ldots\ldots (4)$$

The average rate of energy dissipation per unit area of sea bottom may be obtained by integrating the instantaneous rate over one wave period and dividing by the period as follows:

$$D = 1/T \int_0^T \tau U_h \, dt = 2/T \int_0^{T/2} k \rho U_h^3 \, dt \quad \ldots\ldots (5)$$

From the oscillatory wave theory [O'BRIEN and OTHERS, 1942], the velocity at the bottom is given by

$$U_h = [\pi H/T \sinh (2\pi h/L)][\sin 2\pi \, (x/L - t/T)] \quad \ldots\ldots (6)$$

Substitution of (6) into (5) and subsequent integration yield

$$D_f = k\rho H^3 F\,(h,\ T) \quad \ldots\ldots (7)$$

where F (h, T) might be termed a "dissipation function" and is given by

$$F\,(h,\ T) = - 4\pi^2/3 \ T^3 \, [1/\sinh \, (2\pi h/L]^3 \quad \ldots\ldots (8)$$

Values of the function F (h, T) have been computed from this equation and are presented in Table 1. In accordance with the wave theory the wave length to be used in (8) is a function of the depth. The correct values of h/L for this purpose are presented in Table 2 and were obtained from tables showing the relationship between h/L and h/L_0 [WIEGEL, 1948].

Table 1--Values of F (h, T) computed from (8) and values of h/L from Table 2

Depth	Period			
	6 sec	9 sec	12 sec	15 sec
ft				
5	7.25×10^{-1}	8.04×10^{-1}	8.22×10^{-1}	8.52×10^{-1}
10	2.13×10^{-1}	2.60×10^{-1}	2.82×10^{-1}	2.90×10^{-1}
15	9.50×10^{-2}	1.31×10^{-1}	1.48×10^{-1}	1.57×10^{-1}
20	4.92×10^{-2}	7.88×10^{-2}	9.22×10^{-2}	9.93×10^{-2}
30	1.66×10^{-2}	3.60×10^{-2}	4.53×10^{-2}	5.00×10^{-2}
40	6.14×10^{-3}	1.94×10^{-2}	2.68×10^{-2}	3.07×10^{-2}
50	2.39×10^{-3}	1.14×10^{-2}	1.73×10^{-2}	2.04×10^{-2}
100	1.71×10^{-5}	1.21×10^{-3}	3.51×10^{-3}	5.29×10^{-3}
150	1.04×10^{-7}	1.45×10^{-4}	9.92×10^{-4}	2.01×10^{-3}
200	. . . .	1.59×10^{-5}	3.02×10^{-4}	7.87×10^{-4}
250	. . . .	1.72×10^{-6}	9.11×10^{-5}	3.99×10^{-4}

From (7) it is evident that for a wave train of given period the amount of energy dissipated by bottom friction depends only upon the depth. According to the wave theory, the relative motion between the water particles and the bottom become vanishingly small when the depth exceeds one-half the wave length. Inspection of Tables 1 and 2 also indicates that the energy dissipation becomes appreciable only when the water depth is considerably less than one-half wave length in which case the relative motion between the water particles and the bottom rapidly approach large values and the dissipation function increases rapidly.

Table 2--Values of h/L

Depth	Period			
	6 sec	9 sec	12 sec	15 sec
ft				
5	0.0677	0.0443	0.0331	0.0263
10	0.0986	0.0635	0.0472	0.0376
15	0.1246	0.0788	0.0581	0.0461
20	0.1485	0.0922	0.0676	0.0532
30	0.1941	0.1161	0.0840	0.0661
40	0.2398	0.1379	0.0985	0.0771
50	0.2869	0.1583	0.1118	0.0870
100	0.5446	0.2601	0.1713	0.1294
150	0.8151	0.3685	0.2280	0.1667
200	1.087	0.4840	0.2864	0.2030
250	1.359	0.6023	0.3477	0.2395

In the present analysis the origin for horizontal distance x will be taken at the point where the depth equals one-half the wave length. The power transmitted by the waves in unit time for a crest length of b_0 at the station x = 0, where deep-water conditions prevail, is given by

$$P_0 = (wb_0 H_0^2 \sqrt{L}/7.05)(1 - 4.935 H_0^2/L_0) \ . \quad (9)$$

For increasing values of x (toward shore) the bottom causes a change in wave height and wave length so that for a given wave period these two quantities will be functions of the depth h. Assuming bottom friction to be negligible, the wave height may be computed from the following relation which is obtained from equating the energy of the wave motion corresponding to shallow-water conditions to that corresponding to deep-water conditions.

$$H^2 = 16 b_0 P_0 T/wbL \, (1 - MH^2/L^2) \quad \ldots\ldots\ldots\ldots\ldots\ldots \ (10)$$

where

$$M = 4.935/\tanh^2 (2\pi h/L)$$

If the shoreline is not straight or if the wave crests are not parallel to a straight shoreline, a wave-refraction diagram [JOHNSON, O'BRIEN, and ISAACS, 1948] must be prepared to obtain the trajectory of wave propagation and the variation of b and h along this trajectory. These values may then be plotted as a function of x for subsequent use in the calculations. For wave crests parallel to a straight beach no refraction occurs and b and b_0 are everywhere equal.

In order to estimate the effect of bottom friction, (10) is used to compute a first approximation of H as a function of x. These values of H are then used with (7) to determine the energy dissipation as a function of x, resulting in a plot of the product $D_f b$ versus x. Graphical integration of this curve then yields the energy loss ΔP up to any desired value of x. Subtracting this energy loss from P_0 then gives the energy available from which a new wave height is computed, using the relation

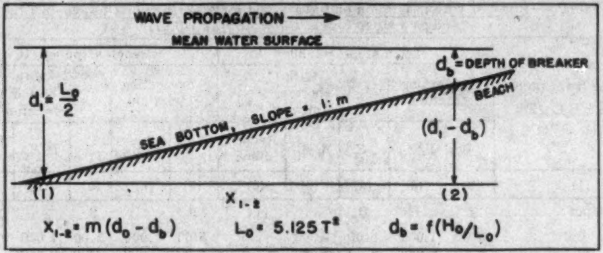
$$P_1 = P - \Delta P = (wH^2 C_G/8)(1 - MH^2/L^2) \quad \ldots\ldots\ldots\ldots\ldots\ldots \ (11)$$

In general, this new value of H will be too small so that successive computations must be employed. About four approximations are required. By taking the ratio of the equation for wave height including bottom friction to that neglecting friction yields a convenient relation for the computations.

$$H_f/H = \sqrt{(P - \Delta P)/P_0 (1 - MH^2/L^2)} \quad \ldots\ldots\ldots\ldots\ldots\ldots \ (12)$$

Strictly speaking, the H occurring under the radical should be taken equal to H_f. However, this expression is small compared to the other terms and for convenience is taken equal to the wave height neglecting friction.

Numerical example--The method outlined above has been applied to the following conditions: Beach slopes, 1/10 and 1/300; wave periods, T = six sec and T = 12 sec; boundary friction factor, k = 0.01; waves parallel to a straight beach, $b = b_0 = 1$ ft; and deep-water wave height, $H_0 = 5$ ft. The geometry of the problem and the various deep-water constants are summarized in Figure 2. The above slopes have been selected because they represent more or less the extremes of conditions that exist in nature. The beaches near the mouth of the Columbia River, for example, approach the 1/300 slope, whereas, beach slopes of 1/10 may be found at certain points on the California Coast.



T SEC.	L_0 FT.	d_0 FT.	H_0 FT.	H_0/L_0	P_0 FT. LB. PER SEC. PER FT.	h_b	X_{1-2} (FT.)	
							m = 10	m = 300,
6	184	92	5	0.0271	3070	7.2	850	25,500
12	738	369	5	0.0068	6160	11.5	3,575	107,250

Fig. 2--Conditions for the computation of the effect of bottom friction on wave height; the depth of breaking h_b was obtained from published data on wave characteristics, Hydrographic Office, 1947)

Following the procedure outlined above, computations were made to determine the effect on wave height for the 12-sec period waves, when the waves moved over beaches with slopes of 1/300 and 1/10 and for the six-sec period waves moving over the 1/300 slope only. The important results of the computations are summarized in Tables 3 and 4 and in Figure 3. Table 3 shows for a 12-sec period wave the effect of bottom slope on the changes in wave height due to bottom friction. Comparison of columns 6 and 11 shows that by the time the waves reach the breaker point the reduction in wave height with the 1/300 slope is about 21 per cent; whereas, the same waves moving over a beach with a 1/10 slope would experience a height reduction of only about one per cent. Since the effect of bottom friction is negligible on the steep beach, calculations for the six-second period waves moving over the 1/10 slope were omitted.

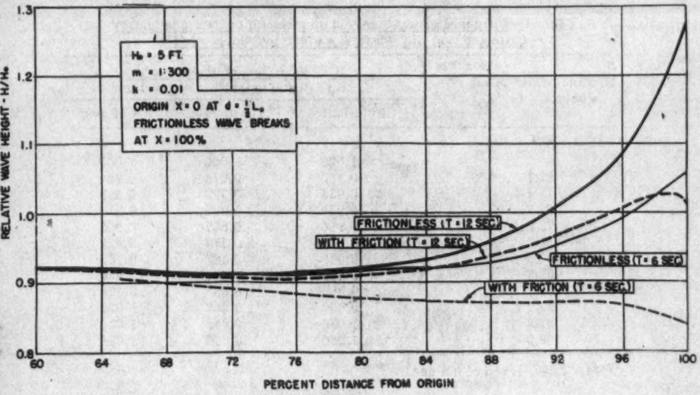


Fig. 3--Effect of bottom friction on wave height

Table 3--Effect of bottom friction on wave height for a 12-sec period wave on a flat and on a steep beach. (H_0 = 5.0 ft, k = 0.01)

Distance from point where h = $L_0/2$	Beach slope = 1/300					Beach slope = 1/10				
	Neglecting friction		With bottom friction			Neglecting friction		With bottom friction		
	H	H/H_0	H	H/H_0	Reduction[a]	H	H/H_0	H	H/H_0	Reduction[a]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
pct	ft		ft		pct	ft		ft		pct
0.0	5.00	1.000	5.00	1.000	0	5.00	1.000	5.00	1.000	0
20.7	4.90	0.980	4.90	0.980	0	4.90	0.980	4.90	0.980	0
41.3	4.68	0.936	4.68	0.936	0	4.68	0.936	4.68	0.936	0
51.7	4.63	0.926	4.63	0.926	0	4.63	0.926	4.63	0.926	0
62.0	4.60	0.920	4.59	0.918	0.2	4.60	0.920	4.60	0.920	0
66.1	4.58	0.916	4.57	0.914	0.2	4.58	0.916	4.58	0.916	0
70.3	4.55	0.910	4.53	0.906	0.4	4.55	0.910	4.55	0.910	0
72.4	4.55	0.910	4.53	0.906	0.4	4.55	0.910	4.55	0.910	0
74.4	4.55	0.910	4.52	0.904	0.7	4.55	0.910	4.55	0.910	0
76.4	4.58	0.916	4.55	0.910	0.7	4.58	0.916	4.58	0.916	0
78.5	4.58	0.916	4.54	0.908	0.9	4.58	0.916	4.58	0.916	0
80.5	4.60	0.920	4.55	0.910	1.1	4.60	0.920	4.60	0.920	0
82.6	4.63	0.926	4.57	0.914	1.3	4.63	0.926	4.63	0.926	0
84.7	4.68	0.936	4.60	0.920	1.7	4.68	0.936	4.68	0.936	0
86.8	4.73	0.946	4.63	0.926	2.1	4.73	0.946	4.73	0.946	0
88.8	4.83	0.966	4.71	0.942	2.5	4.83	0.966	4.83	0.966	0
90.8	4.95	0.990	4.79	0.958	3.2	4.95	0.990	4.95	0.990	0
93.0	5.10	1.020	4.87	0.974	4.5	5.10	1.020	5.09	1.019	0.2
95.0	5.30	1.060	4.97	0.994	6.2	5.30	1.060	5.29	1.059	0.2
97.1	5.60	1.120	5.08	1.016	9.3	5.60	1.120	5.58	1.116	0.4
99.1	6.10	1.220	5.14	1.028	15.8	6.10	1.220	6.06	1.211	0.7
100.0	6.40	1.280	5.07	1.014	20.8	6.40	1.280	6.34	1.269	0.9

[a] Comparison with frictionless wave heights.

Table 4--Influence of wave period on reduction of wave height by bottom friction (H_0 = 5 ft, k = 0.01, and slope = 1/300)

Distance from point where h = $L_0/2$	$\frac{H}{H_0}$ = $\frac{\text{Wave height at point x}}{\text{Wave height in deep water}}$		
	Frictionless[a]	T = six sec	T = 12 sec
pct			
0	1.000	1.000	1.000
21.7	0.980	0.978	0.980
43.4	0.935	0.928	0.935
65.2	0.920	0.905	0.916
73.9	0.910	0.887	0.905
87.0	0.925	0.872	0.929
90.0	0.935	0.867	0.950
91.3	0.945	0.868	0.960
93.5	0.965	0.868	0.978
95.7	0.990	0.867	1.003
97.9	1.020	0.856	1.023
100.0	1.060	0.840	1.014

[a] For wave period of six sec.

The influence of wave period on the reduction of wave height by bottom friction is illustrated by the results presented in Table 4. The results for all three cases are shown graphically in Figure 3, which includes for comparison, the variation in relative wave height for frictionless wave motion.

It is apparent from the curves that height changes due to friction are negligible in the first 60 per cent of the distance from the point where the depth equals one-half the deepwater-wave length; in fact it is only in the last 20 per cent of the total distance that bottom friction becomes appreciable in its effect on wave height. In general, the rate of energy dissipation with distance is small. but it is cumulative and, as in the case of flat beaches, this cumulative effect becomes pronounced when the wave motion occurs over long distances in shallow water.

For the six-second wave the effect of friction is to cause a steady decrease in height to the point of breaking. For the 12-second period wave, on the other hand, the height decreases, due both to friction and to shoaling effects, and then increases to slightly more than the deepwater height. In comparing the changes in wave heights for the cases with and without friction, it is noted that at the point of breaking the effect of friction is to reduce the wave height by approximately 21 per cent for the 12-second wave and approximately 22 per cent for the six-second wave. Note in connection with Figure 3 that the reduction in wave height by friction results in the waves breaking nearer shore than if the motion were frictionless; hence, the percentage reduction in breaker height probably is greater than stated above.

The estimated reduction in wave height due to bottom friction involved four principal assumptions. The first and last assumptions, namely, sinusoidal motion at the sea bottom and plane surface of constant slope, respectively, cannot but have only minor effects on the calculated results. In comparison to the large lateral distances involved, small irregularities, which characterize many flat beaches, tend to average out any secondary effects.

The assumption of a constant friction factor is perhaps more serious. The value used in the above calculations was intended to be closely representative of conditions within the last 20 per cent of the course of the waves toward shore from the point where $d = L_0/2$. Consequently, its value was probably too large for the deeper water but in this region the effects of friction are of very small order compared to those in shallower water. Since the friction factor enters the dissipation equation only to the first power, its value could be in error by ± 50 per cent without appreciably changing the order of magnitude of the results obtained above for wave-height reduction.

In regard to the assumption of negligibly small vertical flow at the sea bottom due to percolation currents, calculation of the maximum possible values for these currents from the theory presented elsewhere [PUTNAM, in preparation] indicates a magnitude of 10^{-3} ft/sec, which is to be compared with the corresponding maximum horizontal velocity of the unobstructed water at the sea bottom of 4.6 ft/sec. Moreover, these two currents are in phase so that when one is zero the other is likewise zero. It accordingly appears valid to assume that small vertical currents, which might disturb the boundary layer, are vanishingly small.

Summary--The above analysis indicates that waves, with periods commonly occurring in the ocean, may experience considerable change in height by bottom friction when they move over relatively flat beaches. The per cent reduction in wave height over a particular slope appears to be independent of wave period. The effect of this reduction in height is to cause a wave to break nearer shore than in the case where no bottom friction is considered.

Acknowledgments--The work summarized in this paper was part of an extensive investigation on waves and surf made in the Department of Engineering, University of California, Berkeley, in cooperation with the Bureau of Ships, U. S. Navy.

APPENDIX 1

Symbols

b = Length along wave crest, ft
C = Wave velocity, ft/sec
C_G = Velocity of energy advance, ft/sec
h = Water depth, ft
D_f = Average rate of energy dissipation by bottom friction per unit area in one wave cycle, ft lbs/sec/sq ft

F = Designates a function
H = Wave height, ft
k = Friction coefficient in the equation, $\tau = k \rho U_d^2$, dimensionless
L = Wave length, ft
m = Bottom slope
p = Spacing of bed ripples, ft
P = Energy transmitted per unit time in crest length b at position x, ft lbs/sec
R = Semi-amplitude of horizontal displacement of water particle at sea bottom
t = Time, sec
T = Wave period, sec
U_h = Fluid velocity at the bottom, ft/sec
w = Unit weight of water, lbs/ft^3
x = Position measured along direction of wave travel
ν = Kinematic viscosity of water, sq ft/sec
ρ = Density of water, slugs/ft
τ = Tractive force per unit area, lbs/ft^2
Subscripts 0 refer to deep water conditions

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INFILTRATION, SOIL MOISTURE, AND LAND-USE RELATIONSHIPS WITH REFERENCE TO SURFACE RUNOFF

Leonard Schiff and F. R. Dreibelbis

Abstract--The major development in this paper is a method for determining rates of water movement within the soil profile on watersheds under natural conditions. The method uses rainfall rates or infiltration curves as the supply of water to the soil and field measurements of soil-moisture changes. The major objective was the determination of relationships between infiltration, soil moisture, and surface runoff on watersheds representing two soil types of different hydrologic characteristics and in three vegetal covers. Information was developed on the effect of soil properties and land use upon such relationships.

The amounts of water taken up by successive inch increments of soil depth during storms were established by soil-moisture measurements. The time required for each of these amounts to accumulate was determined from the accumulated infiltration curve, or from rainfall minus interception storage when no runoff occurred. Analyses indicate the velocity of water moving through the soil under various conditions, particularly differences in available storage space. Transmission rates or velocities as high as ten in/hr were obtained for the topsoil or plow layer. For a number of storms, water reached the subsoil shortly after runoff began. After water reached the subsoil, the rates at which the remaining topsoil storage was exhausted were deducted from the infiltration rates and the percolation rates at the bottom of the topsoil established. Percolation rates did not exceed 0.60 in/hr. Using percolation rates as the supply, transmission rates through the subsoil were established. Transmission rates did not exceed 1.50 in/hr for the subsoil. As saturation was approached, rates of infiltration decreased until they approached a constant rate at saturation and the low transmission rates in the subsoil became the controlling factor. Infiltration curves, percolation curves, and transmission rates are illustrated and findings interpreted in the light of soil properties and land use.

Introduction

The major development in this paper was the use of infiltration curves and rainfall rates as the supply of water to the soil mass for the determination of rates of water movement within the soil mass. The major objective was the determination of relationships between infiltration, soil moisture, and surface runoff. Information was developed concerning the effect of soil properties and land use upon such relationships.

The value of such information has often been stated by those seeking the conservation of soil and water and by those concerned with the growth of crops, with irrigation, drainage, water supply, flood control, and similar work. Considerable literature on various phases of this subject exists, such as the work of members of the Committee on Infiltration of the American Geophysical Union and such basic information that has been contributed by MUSGRAVE and NORTON [1937] and others.

Studies by the writers indicate that, although many factors are involved, a certain few seem to exert the most influence on water movements. The number and effect of important factors may vary in different localities. Among the factors that will be mentioned in this paper is the ability of certain soils to absorb and transmit water. It is believed that progress will be made as soils are grouped as to their hydrologic characteristics, primarily permeability. In the past, emphasis has been placed on fertility and productivity ratings. In preparing ratings of this type information was obtained on texture and structure. Such information is valuable in grouping soils as to water movements. Another factor is land use. The influence of land use upon the delivery of water to the soil surface and upon water movements within the soil during storms is a consideration. The influence of land use on evapotranspiration and soil properties and conditions over a period of time is another consideration. Another factor is the influence of rainfall characteristics on water movements. A standard method of classifying rainfall according to characteristics of storms would be valuable. Classification of rainfall has been attempted by HORNER and JENS [1941], SCHIFF [1943], and others. The relationships that might be developed between a grouping of soils based on water movements and rainfall characteristics for various localities would enrich the fields concerned with hydrologic problems.

Experimental procedure

This work was conducted at the North Appalachian Experimental Watershed located about ten mi north of Coshocton, Ohio. The area is typical of the general farming area of the North Appalachian physiographic province that comprises eastern Ohio, western Pennsylvania, northeastern Kentucky, and western West Virginia. The experimental watershed lies within the humid region. The mean annual precipitation is 40 inches. Rainfall is moderately intense. The average annual snow depth is about 20 inches.

Four small watersheds were selected for this study, three in a four-year rotation of corn, wheat, meadow, meadow; and one in permanent pasture. For any one of these watersheds the soil type, the crop, and the land use are uniform. Most of the physical factors, other than those given in Table 1, are reasonably similar on all watersheds. Differences in physical factors are in favor of conclusions reached. For example, Watershed 123 has had more runoff and higher rates of runoff than Watershed 109, yet such factors as slope, shape, and drainage pattern are conducive to more runoff and higher rates on the latter. Runoff differences were due largely to the considerable difference in permeability of portions of the two soil profiles. The considerable difference in permeability of the two soil profiles increased the value of this study.

Rainfall was measured by recording rain gages. Runoff was composed primarily of surface flow and was measured in precalibrated flumes equipped with water-stage recorders. Hydrograph recessions, the absence of seepage around the deep walls supporting the flumes, and soil-moisture determinations indicate little, if any, subsurface lateral flow in the portion of the soil profile considered.

Soil moisture was determined on Watersheds 109, 123, and 104, using gypsum blocks and by field sampling (gravimetric method). A recording tensiometer was also used on Watershed 109. Detailed information on soil moisture was obtained in the 0-1, 1-3, 3-5, and 5-7 inch depths representing the topsoil, and the 7-10 and 10-14 inch depths representing the upper subsoil. An installation of gypsum blocks was placed in triplicate, side by side, at each of the above depths at a representative location determined by soil-moisture measurements made during previous years. Additional installations at four locations on each watershed provided information on soil moisture to represent the profile to a depth of 40 inches. Moisture determinations were frequently made before and after storms and the data expressed on a volume basis. In general, reliable data were obtained from the gypsum blocks in the range of soil moisture below field capacity. Tensiometer data were used only in the range above field capacity. Frequently, gravimetric determinations were used to check both methods, particularly at the end of storm periods. The depth divisions were based upon the profile characteristics of these soils. The Muskingum and related series, which are relatively immature, do not have as sharply defined horizons as more highly developed soils. Detailed information on the profile characteristics of the soil types studied were previously presented by DREIBELBIS and POST [1940, 1943].

Data were also obtained on depths of frost penetration. Percolation values at the eight-foot level were determined by monolith lysimeters. Evapotranspiration was determined from changes in soil moisture and from data obtained from weighing lysimeters adjacent to Watersheds 109, 123, and 104.

The data obtained from Watersheds 109, 123, and 104 gave consistent and reasonable results. This led to the estimation of soil moisture on Watershed 103 so the study would have a wider land-use application.

Terms and symbols used are listed below.

Infiltration--The passage of water through the surface of the soil into the soil mass; f, infiltration rate; f_p, infiltration capacity, that is, the rate at which infiltration would take place at any instant were the supply to equal or exceed this capacity; F, accumulated infiltration.

Transmission--The movement of water downward through a given depth within the soil mass; t_{ts}, transmission rate (velocity) within the topsoil; t_{ss}, transmission rate (velocity) within the subsoil.

Percolation--The water passing a given level within the soil mass; g_{ss}, percolation rate at the top of the subsoil; S_{ts}, storage capacity available at a given time within the topsoil; sd_{ts}, storage depletion rate within the topsoil; SD_{ts}, storage depleted or exhausted in a given period of time within the topsoil; S_{ss}, storage capacity available at a given time within the subsoil; sd_{ss}, storage

Table 1--Description of watersheds selected for study, 1946

Watershed No.	Area	Average land slope	Soil	Drainage	Land use	Crop and operation
	ac	pct				
109	1.69	12.7	Muskingum silt loam (shale origin)	Well-drained	Wheat, improved (4-year rotation: corn, wheat, meadow, meadow)	Cultural practices: Jan. 19 and Mar. 11, spread manure; Mar. 22, seeded legumes; July 9, cut wheat; Aug. 13, mowed Height wheat: Mar. 6, two inches; June 5, 36 inches; July 8, 40 inches; July 9, wheat cut, grass, clover, and weeds six inches or less
123	1.37	5.8	Keene silt loam	Slowly permeable	Wheat, improved (4-year rotation: corn, wheat, meadow, meadow)	Same as watershed 109 to all practical purposes
103	0.65	11.3	Keene silt loam	Slowly permeable	Corn, contour improved (4-year rotation: corn, wheat, meadow, meadow)	Cultural practices: April 24, plowed; April 30 and May 15, disked; May 24, harrowed corn ; June 7, 25, and July 2, contour cultivated; Sept. 18, corn cut; Sept. 25, 27, spread three tons lime per acre, disked; Sept. 27, wheat planted Height corn: June 5, six inches; June 16, 11 inches; July 8, 36 inches; July 25, to eight ft; Sept. 6, 11 ft; Sept. 18, corn cut
104	1.33	20.7	Muskingum silt loam (sandstone origin)	Well-drained	Permanent pasture, improved	Cultural practices: Mar. 20, drilled fertilizer and grass seed; May 1, spread four tons lime per acre; May 12-22, grazed; Aug. 13, mowed weeds; Sept. 4, drilled 400 lb, 20 pct phosphate fertilizer Height grass and weeds: Mar. 6 to June 5, one inch to three inches; June 26 to Aug. 8, seven inches to 15 inches; Aug. 22 to Oct. 23, two inches to four inches; Nov. 20 on, one inch

depletion rate within the subsoil; SD_{SS}, storage depleted or exhausted in a given period of time within the subsoil; P, accumulated precipitation; S_1, interception storage, that is, rainfall absorbed and stored by vegetal cover. (Rainfall depth minus interception storage equals depth of water reaching the soil surface.)

For the sake of clarity infiltration rate and percolation rate may be considered a depth of water over a given area passing a given soil level in a specific period of time. Transmission rate may be considered a linear velocity of water through a given depth of soil.

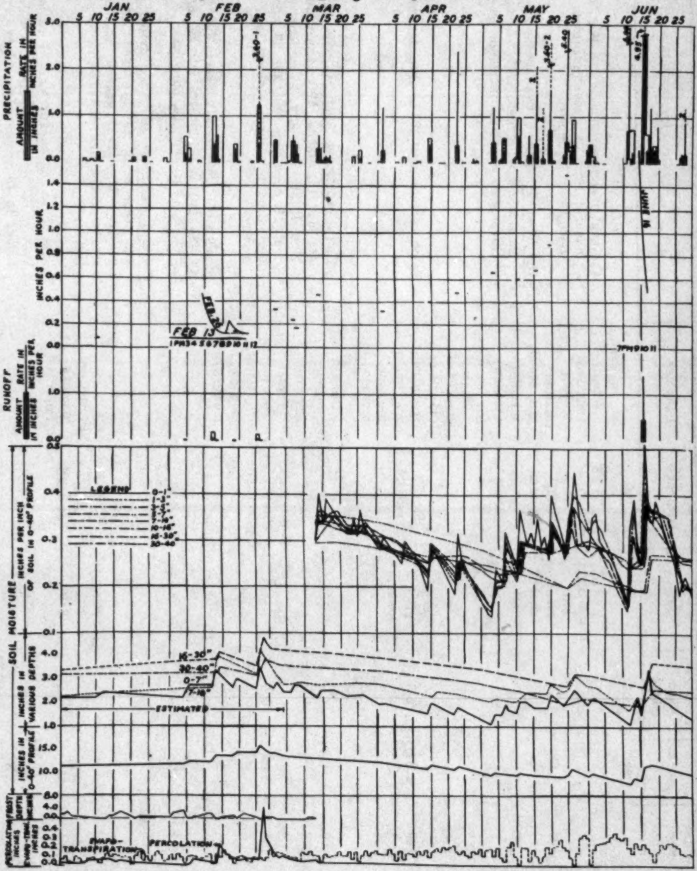

Fig. 1--Basic hydrologic data and infiltration curves for Watershed 109, January to June 1946

Table 2--Inches of soil moisture in various depths of soil, storm of June 16, 1946

Item	Soil moisture for depth ranges in inches									
	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-9.9
1	2	3	4	5	6	7	8	9	10	11
Near end of storm	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.50	0.50	0.42
Before storm	0.31	0.31	0.31	0.26	0.26	0.29	0.28	0.30	0.30	0.27
Gain for depth range	0.20	0.20	0.20	0.25	0.25	0.22	0.23	0.20	0.20	0.15
Total gain entire depth	0.20	0.40	0.60	0.85	1.10	1.32	1.55	1.75	1.95	2.10[a]

[a] Accumulated infiltration for storm 2.10 inches

Table 3--Transmission rate within the topsoil, storm of June 16, 1946

Time		Accumulated precipitation P	Interception storage S_i	Accumulated infiltration F	Increment of F	Gain	Soil moisture			
							Depth reached	Increment depth moved	Time increment	Transmission rate t_{ts}
1		2	3	4	5	6	7	8	9	10
h	m	in	in	in	in	in/in	in	in	min	in/hr
20	45	0	0	0	0	0	0	0	0	0
20	49	0.15	0.15	0	0	0	0	0	0	0
21	00	a	...	0.20	0.20	0.20	1	1	11	5.5
21	06	...	...	0.40	0.20	0.20	2	1	6	10
21	10	...	...	0.60	0.20	0.20	3	1	4	15
21	165	...	...	0.85	0.25	0.25	4	1	6.5	9.2
21	27	...	...	1.10	0.25	0.25	5	1	10.5	5.7
[b] 21	31	...	...	1.18	1.18	1.18	7	7	42	10

[a] Values not shown after 20^h49^m since F was used to develop transmission rates.
[b] Totals from 20^h49^m to 21^h31^m when water reached the subsoil, using a transmission rate of ten inches per hour shown in the last column.

Table 4--Transmission rate within the subsoil, storm of June 16, 1946

Time						Average percolation g_{ss}	Water supply to top of subsoil		Gain increment	Soil moisture		Time required		Transmission rate t_{ss}
From		To		Interval			Increment	Total		Depth reached	Depth moved			
1		2		3		4	5	6	7	8	9	10		11
h	m	h	m	hr	min	in/hr	in	in	in	in	in	hr	min	in/hr
20	31	23	31	2	0	0.10	0.20	0.20	0.20	8	1	2	0	0.5
23	31	02	51	3	20	0.06	0.20	0.40	0.20	9	1	3	20	0.3
02	51	06	11	3	20	0.045	0.15	0.55	0.15	9.9	0.9	3	20	0.25

Results

Basic data--Figure 1 is included mainly to illustrate the form of plotting basic data, such as rainfall, surface runoff, soil moisture, percolation, frost and evapotranspiration, and the infiltration curves that were developed.

Concept and analyses of data--The concept and methods of analyses upon which most of this paper is based are described using the storm of June 16, 1946, for Watershed 123, as an example.

(1) Accumulated infiltration was taken as the supply of water to the soil mass. Accumulated infiltration and corresponding rates of infiltration were determined by methods developed primarily by SHARP and HOLTAN [1942] and HOLTAN [1945]. Infiltration rates are shown in Figure 1

for all runoff periods occurring from January through June 1946 on Watershed 109. A horizontal line drawn across a block for a specific day, in the infiltration section of the figure, represents the maximum infiltration rate on that day. This rate might have been greater had the rate of rainfall been greater.

(2) The transmission rate or velocity of water through a given depth within the topsoil mass was determined from the amount of water supplied and the increase in soil moisture. For example, Table 2 shows a gain in soil moisture from 0.31 inch to 0.51 inch (saturation) for the depth range of 0-1 inch. Thus, 0.20 inch of water was absorbed in 1-inch depth of soil. Table 3 shows that the water supply or accumulated infiltration, F, of 0.20 inch occurred between 20^h49^m and 21^h00^m, in 11 min. Since the gain of 0.20 inch occurred through a depth of one inch and was supplied in 11 min, water must have moved one inch in 11 min. This is equal to a transmission rate, t_{ts}, or velocity, of 5.5 inches per hour. Table 2 shows a gain in soil moisture of 0.20 inch for the depth range of 1-2 inches. Between 21^h00^m and 21^h06^m, 0.20 inch entered the surface of the soil and 0.20 inch must have moved from the 0-1 inch depth to the 1-2 inch depth. This represents a water movement through the 0-1 inch depth of 0.20 inch and a gain of 0.20 inch in the 1-2 inch depth. This is equivalent to a water movement of one inch in six min or a transmission rate of ten in/hr. This procedure was applied to other successive increments of depth to obtain the transmission rates shown in the last column of Table 3.

For these soils and for the storms analyzed, soil-moisture data and computations indicate that water reaches the subsoil shortly after the time runoff starts and somewhat before the topsoil is completely saturated. Exceptions to this have been found during gentle rains. A considerable supply of water seems to establish somewhat of a saturated front that moves rapidly through the topsoil. In view of these considerations, a rate of ten in/hr was taken as the transmission rate through the topsoil, which is slightly greater than the average rate that may be determined from Table 3, between 20^h49^m and 21^h27^m. A rate of ten in/hr indicates that the soil had not quite reached saturation between 20^h49^m and 21^h27^m. Saturation occurred after water had reached the subsoil as discussed later.

(3) At a transmission rate of ten in/hr, water moved through the seven-inch topsoil and reached the subsoil in 42 min, at 21^h31^m (20^h49^m, time F began in Table 3, plus 42 min). Surface runoff started at 21^h20^m. (For portions of the watersheds where the topsoil may be less than seven inches deep, water would have reached the subsoil sooner than 21^h31^m. However, such refinements are unnecessary to answer many practical hydrologic problems.) The soil moisture gain at 21^h31^m, when water reached the subsoil, was 1.18 inches (see Table 3). To reach saturation the total gain for the topsoil 0-7 inches (see Table 2), was 1.55 inches. Therefore, it required 1.55 minus 1.18 inches or 0.37 inch to saturate the topsoil after 21^h31^m.

(4) After water reached the subsoil at 21^h31^m there were two movements to be considered, the saturation of the topsoil which is the exhaustion of the remaining topsoil storage space of 0.37 inch and the percolation of water from the bottom of the topsoil into the subsoil. The infiltration rate minus the rate of exhaustion of the topsoil storage space is equal to the percolation rate. In accordance with the dictates of the infiltration curve the accumulation of soil moisture within the topsoil mass, until 0.37 inch was gained or storage space depleted, SD_{ts}, is shown along the infiltration curve, in this case f_p curve since capacity rates occurred, Figure 2. For example, the SD_{ts} value of 0.107 inch is shown at 21^h41^m. This was obtained by dividing the ordinate between 21^h31^m and 21^h41^m (1.11 minus 0.80 = 0.31) by the ordinate between 21^h31^m and the lowest rate of infiltration reached (1.11 minus 0.04 = 1.07). This ratio (0.31 divided by 1.07) is 0.29 or 29 per cent. The total storage space to be depleted, 0.37 inch, multiplied by 29 per cent is the value 0.107 inch. Other SD_{ts} values shown were similarly obtained.

The SD_{ts} values were then used to obtain storage space depletion rates and percolation rates. For example, by 21^h41^m, 0.107 inch had been accumulated and by 21^h51^m 0.197 inch had been accumulated. This represents a gain of 0.09 inch in ten min, or an average storage space depletion rate, sd_{ts}, of 0.54 in/hr. The percolation rate g_{ss}, is equal to the f_p value of 0.67 in/hr minus the sd_{ts} value of 0.54 in/hr or 0.13 in/hr as plotted at 21^h46^m. Other points of the g_{ss} curve were similarly established. The difference between the f_p curve and the g_{ss} curve at any specific time is the sd_{ts} at that time. The cross-hatched portion between the f_p curve and the g_{ss} curve represents the total amount of storage space depleted within the topsoil, SD_{ts}, after water had reached the subsoil.

The f_p curve represents water supplied for exhaustion of topsoil storage space and for percolation to the subsoil (g_{ss} curve), consequently its values are higher and there is less abrupt change in slope. When exhaustion of topsoil-storage space occurs or saturation reached, the f_p curve and g_{ss} curve coincide. As previously mentioned the g_{ss} curve is controlled primarily by the transmission rate in the subsoil, a key factor in runoff.

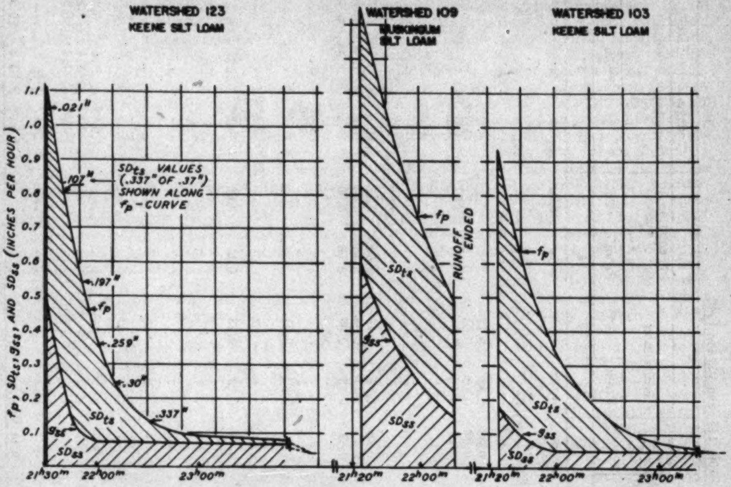

Fig. 2--f_p, SD_{ts}, and SD_{ss} beginning at time water reached subsoil, storm of June 16, 1946

(5) Just as the f_p curve can be considered a supply of water for the topsoil, the g_{ss} curve can be considered a supply for the subsoil. Total infiltration was 2.10 inches, 1.55 inches of which satisfied topsoil storage. The remainder of 0.55 inch moved into the subsoil and as shown in Table 2.the soil was saturated to a depth of about ten inches. Table 4 presents transmission rates, t_{ss}, for a portion of the subsoil. These rates progressively decreased from 0.5 to 0.25 in/hr and probably indicate the influence of swelling soil colloids. A bottleneck is indicated, transmission rates are low, and the exhaustion of storage space in the subsoil takes place at a much lower rate than in the topsoil. The difference between the g_{ss} curve and the base line at any specific time is the sd_{ss} at that time. The cross-hatched portion between the g_{ss} curve and the base line on Figure 2 represents the total amount of storage space depleted within the subsoil, SD_{ss}, from the time water was supplied by the storm investigated and the end of runoff.

Analyses of storms--Figure 2 also presents f_p, SD_{ts}, g_{ss}, and SD_{ss} values for Watersheds 109 and 103 for the storm of June 16, 1946. At any specific time values of sd_{ts} may be obtained by taking the difference between the f_p curve and the g_{ss} curve, values of sd_{ss} by taking the difference between the g_{ss} curve and the base line. These values were established using the methods given in the analysis for Watershed 123. Table 5 presents a summary of data and results of analyses for Watersheds 109, 123, and 103 for a number of storms occurring in 1946.

Interpretation

Available storage space, soil-water movements, runoff--No runoff occurred on Watersheds 109 and 123 whenever the available storage space in the topsoil was greater than the precipitation. Columns 3, 4, and 5 of Table 5 show that space available for the storage of water is almost always smaller on Watersheds 123 and 103 (Keene silt loam) than on Watershed 109 (Muskingum silt loam). The Keene silt Loam of Watersheds 123 and 103 being slowly permeable had less available storage space prior to storms than the well-drained Muskingum silt loam of Watersheds 109 and 104. Accounting for differences in rainfall, infiltration is generally lower on the Keene silt loam of Watersheds 123 and 103 and runoff is greater. Drainage is best and available storage space generally greater on the Muskingum silt loam of sandstone origin on Watershed 104.

Table 5--Analyses of storms for Watersheds 109, 123, and 103 for 1946

Water-shed No.	Date	Storage available[a]			Precip-itation P	Runoff		Total infil-tration F	Time[b] water reached subsoil	Subsoil gain at end of runoff	Rate[b]				Transmission rate[b]		
		Topsoil 0-7" S_{ts}	Subsoil 7-14" S_{ss}	Total 0-14"		Time began	Total				Infiltration f		Percolation at top of subsoil g_{ss}[c]		Topsoil t_{ts}	Subsoil t_{ss}	
											From	To	From	To		From	To
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
		in	in	in	in	h m	in	in	h m	in	in/hr	in/hr	in/hr	in/hr	in/hr	in/hr	in/hr
109	Feb. 13	0.82	1.33	2.15	1.00	13 21	0.19	0.78	....	...	...	...	...	...	...	...	...
123	Feb. 13	0.77	0.98	1.75	1.02	14 14	0.18	0.81	....	...	...	...	...	...	...	...	...
103	Feb. 13	0.77	0.77	1.54	1.01	13 50	0.06	0.92	....	...	...	...	...	...	...	...	...
109	Feb. 26	0.97	0.84	1.81	1.25	18 20	0.11	1.08	18 30	0.08	0.22	0.12	...	...	5.3^e	...	...
123	Feb. 26	0.77	0.84	1.61	1.23	18 36	0.70	0.50	18 40	0.08	0.10	0.03	...	...	5.2^e	...	...
103	Feb. 26	0.77	0.77	1.54	1.27	18 30	0.35	0.90	18 26	0.12	0.18	0.04	...	...	6.3^e	...	...
109	June 12	2.46	1.68	4.14	1.45	....	0	1.33	....	...	...	...	...	...	10.0	...	...
123	June 12	2.22	1.54	3.76	1.51	....	0	1.36	....	...	...	...	...	...	10.0	...	...
103	June 12	1.68	1.14	2.82	1.38	....	0	1.35	....	...	...	...	...	...	10.0	...	...
109	June 16	2.08	1.70	3.77	3.40	21 20	0.47	2.88	21 25	0.26	1.35	0.49	0.60	0.15	10.0	1.50	0.75
123	June 16	1.55	1.18	2.73	3.61	21 20	1.48	2.10	21 31	0.55	1.11	0.04	0.46	0.04	10.0	0.50	0.25
103	June 16	1.35	1.11	2.46	3.65	21 17	1.77	1.85	21 26	0.51	0.93	0.05	0.18	0.05	10.0	0.38	0.29
109	July 11	2.52	1.78	4.30	1.94	....	0	1.89	....	...	...	...	...	...	5.0^e	...	...
123	July 11	2.50	1.78	4.28	1.76	....	0	1.71	....	...	...	...	...	...	3.8^e	...	...
103	July 11	2.14	1.54	3.68	2.07	17 53	0.08	1.93	18 13	0	0.99	0.41	...	...	10.0^d	...	...
109	July 20	2.08	1.36	3.14	1.46	....	0	1.39	....	...	...	...	...	...	7.5^e	...	...
123	July 20	2.22	1.69	3.91	1.50	....	0	1.43	....	...	...	...	...	...	8.5^e	...	...
103	July 20	1.38	1.61	2.99	1.53	17 22	0.21	1.25	17 22[d]	0.14	0.73	0.23	0.11	0.06	4.5^e	...	...
109	Aug. 6	2.29	1.64	3.93	1.06	....	0	1.00	....	...	...	...	...	...	...	...	...
123	Aug. 6	1.73	1.26	2.99	0.98	....	0	0.92	....	...	...	...	...	...	...	...	...
103	Aug. 6	1.25	1.36	2.61	1.03	19 00	0.02	0.90	....	...	...	...	...	...	...	...	...
109	Aug. 15	2.67	1.92	4.79	1.03	....	0	1.00	....	...	...	...	...	...	...	...	...
123	Aug. 15	2.37	1.50	3.87	1.10	....	0	1.07	....	...	...	...	...	...	...	...	...
103	Aug. 15	1.75	1.57	3.32	1.07	11 34	0.01	1.03	....	...	...	...	...	...	...	...	...
109	Oct. 17	2.31	2.49	4.80	1.86	....	0	1.82	....	...	...	...	...	...	0.7^e	1.4	0.9
123	Oct. 17	2.04	1.50	3.54	1.85	....	0	1.81	....	...	...	...	...	...	0.8^e	1.4	0.9
103	Oct. 17	2.21	2.42	4.63	1.84	....	0	1.81	....	...	...	...	...	...	0.8^e	1.4	0.9
109	Nov. 25	1.01	1.14	2.15	0.97	....	0	0.91	....	...	...	...	...	...	...	...	...
123	Nov. 25	1.01	1.02	2.63	0.96	....	0	0.90	....	...	...	...	...	...	...	...	...
103	Nov. 25	0.79	1.15	1.94	0.94	12 56	Trace	0.90	13 00	0.11	...	...	...	...	2.0^e	1.3	0.9

[a] Estimated for Watershed 103. [b] Computed; leaders represent data omitted because of insufficient magnitude to warrant computation. [c] Rates shown are from the time water reached subsoil (no entry is given if this time was not computed) to the time runoff ended. [d] Assumed. [e] Water supply is limiting

The analyses indicate that the topsoil of both the Muskingum silt loam and Keene silt loam absorbed water during high intensity storms when there was sufficient available storage space. The analyses show that the soils absorbed rainfall at rates between one and six in/hr during various storms in 1946. For this to occur, resulting transmission rates in the topsoil had to be as high or higher than ten in/hr. Analyses also indicate that such high rates existed until water reached the subsoil. The time that water reached the subsoil (see Column 10) is close to the time that runoff began (see Column 7). In other words, much of the storage space available in the topsoil may be used because high transmission rates therein permit its use before runoff begins. Little use is made of the available storage in the subsoil (see Col. 4) because of the low transmission rates in the subsoil (see Col. 18). Rates of infiltration are greatly reduced from the time water reaches the subsoil until runoff ends (see col. 12 and 13). A bottleneck is created by the low transmission rates in the subsoil as shown (see col. 17 and 18). After water reached the subsoil and the low transmission rates of the subsoil became the controlling factor, rates of runoff increased even when rates of rainfall had decreased. Comparisons of various rates are shown graphically in Figure 2.

Soil properties, soil-water movements, runoff--Data on soil properties furnish basic information pertaining to the storage and movement of soil water. A combination of some of these properties largely explains why the Muskingum silt loam on Watersheds 109 and 104 is well-drained while the Keene silt loam on Watersheds 123 and 103 is less permeable resulting in only fair drainage. The greatest contrast in the profile characteristics of these soils appears in the subsoil.

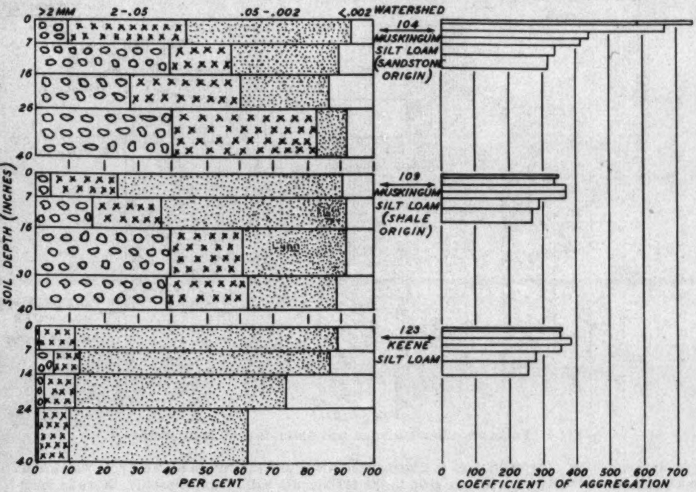

Fig. 3--Mechanical analysis and coefficient of aggregation

Data on the mechanical analysis and on the coefficient of aggregation appear in Figure 3. The coefficient of aggregation is a single value expression of soil aggregation and is inversely proportional to the specific surface area of the aggregates. It is an index of soil structure. The Muskingum silt loam (sandstone origin) has a large percentage of coarse particles throughout the profile, particularly parent material fragments greater than two mm which is favorable to rapid drainage. The Keene silt loam, on the other hand, has a high percentage of silt and clay particles, particularly in the subsoil. The swelling and shrinking properties of the latter exert a considerable influence on soil-water movement. The Muskingum silt loam over shale resembles that of sandstone origin but is somewhat heavier in texture.

Wide differences in hydrologic characteristics have been noted in sections of these profiles. It may be observed in Figure 3, however, that the coefficient of aggregation of the topsoils of the Keene silt loam and the Muskingum silt loam is nearly the same. Since vegetal cover and tillage exert considerable influence on aggregation the similarity of the results is not surprising because the land use practices on these two areas have been the same since 1936. The higher aggregation in the 3-7 inch depth on the rotation watersheds reflects the influence of the plow in turning over the more highly aggregated layer at the surface (before plowing) to the 3-7 inch depth. On Watershed 104, which has been in permanent pasture for a long time, the effect of sod crops on aggregation is evident. This soil has by far the greatest coefficient of aggregation of any soil studied, the aggregation decreasing consistently with depth.

The form and distribution of soil water for the various layers in the 0-40 inch profile appears in Figure 4. The minimum field soil water represents the lowest soil moisture content found under field conditions during the nine-year period, 1937-1946. In the topsoils it is essentially the same as the hygroscopic moisture. However, in the subsoils it rarely, if ever, becomes as low as the hygroscopic moisture in this region. All the volume above the minimum field soil water is the active soil water and represents potential available storage space, the amount available depending upon the moisture present in the soil. It includes all the water that may be accumulated or released under field conditions. This includes water removed from the soil both through percolation and evapotranspiration. The quantities of hygroscopic water and the minimum field soil water are much greater in the Keene silt loam than in the Muskingum soils. Consequently, there is much less available storage space in the former. When soils are nearly saturated, as they frequently are during late winter or early spring, runoff generally occurs much sooner on the Keene silt loam than on the Muskingum soils. When the soils are very dry, as often happens in late summer or early fall, more storage space is available and infiltration rates and amounts in the Keene silt loam approach those in the Muskingum soils.

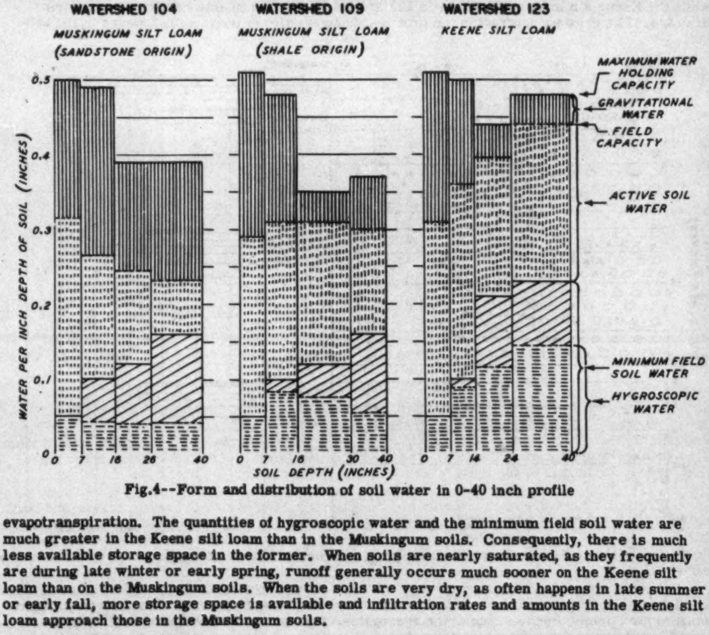

Fig.4--Form and distribution of soil water in 0-40 inch profile

The maximum water holding capacity is the theoretical amount of water the soil could hold if all the pores were filled with water. For the various topsoils this varies little; for the subsoils considerably. The gravitational water is the amount of water held between field capacity and saturation and is the water that moves freely through the profile. This amount varies considerably among the various layers in the profiles studied.

The pore-size distribution curves in Figure 5 represent the expression of soil moisture on an energy basis. The range of 0-500 cm tension covers the range of field capacity to saturation, and includes essentially all of the gravitational water. The curves show that the lowest tensions represent the larger pores. The approximate dividing line between capillary and non-capillary pores lies at approximately 40 cm tension (pF 1.6). All the soil water between 0 and 40 cm tension is held rather loosely and drainage is rapid. Above 40 cm drainage decreases. As the curve approaches 500 cm (pF 2.7) the moisture is held more firmly and drainage diminishes accordingly. While the pore-size distribution curves of the topsoil of the Muskingum silt loam and Keene silt loam are nearly the same, those of the subsoil show a great contrast in water-holding ability. In the field this is reflected in greater runoff on the Keene silt loam than on the Muskingum silt loam when the topsoils are near saturation. The subsoil of the former holds more water at the same tension than the subsoil of the latter where it drains more readily.

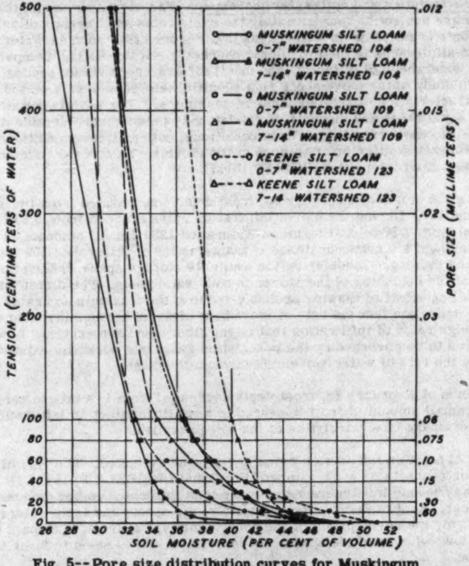

Fig. 5--Pore size distribution curves for Muskingum and Keene silt loam

Although no data have been presented showing the direct influence of organic matter and plant residues on soil-water movement, it should be emphasized that the presence of these materials in the topsoil is of considerable importance in soil-water relationships. They are a major factor in characterizing the top soil as a favorable medium for promoting infiltration and rapid soil-water movement.

Land use--Analyses of these storms show rather conclusively that soil characteristics exert an important influence on storage space and movement of water. Soil characteristics may be affected by land use, such as through the addition of organic matter and plant residues. Land use also plays an important part during and between storms. For example, an important factor in the depletion of soil moisture or the creation of storage space is evapotranspiration. During much of the period of high-intensity storms Watershed 103, corn on Keene silt loam, had less space available for the storage of water than Watershed 123, wheat on Keene silt loam. The transpiration by corn during this period when corn plants were very small was much less than that of wheat when this crop was close to maturity. Consequently, with more soil moisture and less space available to store water, Watershed 103 had greater runoff.

Evapotranspiration in the short periods between many of the storms is somewhat greater on the Keene silt loam, however, not nearly enough to compensate for the better drainage of the Muskingum silt loam. Consequently, available storage space is almost always less on the former.

Land-use practices that promote the development of the topsoil increase the storage space available for rapid soil-water movement and high infiltration rates will prevail for a longer period of time. An additional inch or two of topsoil may, at times, mean the difference between surface runoff and no surface runoff. Reduction in surface runoff will reduce erosion.

Rainfall characteristics and soil-water movement--For any given storm, the watersheds mentioned herein are subject to approximately the same rates and amounts of rainfall. Differences in rates and amounts of runoff from watersheds in the same crop, such as Watersheds 109 and 123, are due largely to differences in the hydrologic characteristics of soils. Comparisons may also be made between watersheds of different land use if differences, such as sealing, are reasonably accounted for. To study water movements on a specific watershed over a period of time the influence of the characteristics of rainfall must be considered. For any given watershed two storms of approximately equal rates and amounts of rainfall may produce considerable differences in rates and amounts of runoff even though crop conditions, soil-moisture conditions, and soil properties were reasonably similar prior to each of the storms. This is due primarily to the difference in the sequence of intensities [SCHIFF, 1943].

Frost--During the storm of February 13, frost depth was reduced from two inches to zero on Watersheds 109 and 123. During the storm, infiltration rates dropped from 0.09 to 0.07 in/hr on Watershed 109 and from 0.20 to 0.04 in/hr on Watershed 123. Runoff amounts on both watersheds were about the same and the better drainage characteristics of Watershed 109 were probably offset by the frost and thawing. Considering the available storage space, infiltration rates should have been higher at the beginning of the storm on both watersheds. The direct influence of frost as well as the puddling effect of thawing probably reduced the transmission rates through the topsoil. There is an indication that the rate of movement of water through the frost was low enough to prevent initial high rates of infiltration that might otherwise have existed. Low final rates of infiltration appeared to be governed by the percolation rates that normally exist during saturation rather than by the rate of water movement through the frost.

During the storm of February 26, frost depth decreased from 1/2 inch to zero on Watersheds 109 and 123. The small amount of frost appeared to have little effect on infiltration rates, consequently normal drainage characteristics of the soil prevailed.

The influence of frost on infiltration rates is yet to be evaluated. The type of frost appears to be a factor, whether concrete or honeycombed [POST and DREIBELBIS, 1942]. It is believed that the concrete type may reduce infiltration rates more than the honeycombed type due to the greater density of the former. Root material, organic matter, air space, and temperatures slightly below freezing seem to favor the development of the honeycomb type of frost. Compact soil, high soil-moisture content, low volumes of air space, and low temperatures seem to favor the development of the concrete type.

Some important points

Below are points that seem important enough to repeat or are derived from results of analyses.

(1) For the soil types studied and for soils with similar hydrologic characteristics, runoff rarely occurs if the available storage space in the topsoil is not exhausted by the total infiltration, except under unusually high rates of rainfall or when sufficient sealing takes place. Potential storage space can only be insured when land-use practices build and conserve the soil.

(2) The topsoil of both the well-drained Muskingum silt loam and the slowly permeable Keene silt loam can absorb a high rate of rainfall provided the initial soil-moisture content is not too high. Good land-use practices probably improve conditions in the topsoil of the Keene silt loam to the point where transmission rates approached those in Muskingum silt loam. After runoff begins, infiltration rates drop even though gravitational water has not reached the subsoil. At times this is evidenced by the higher soil-moisture content of the upper portion of the topsoil. The pores seem to clog with water containing variable amounts of soil colloids, the greater the colloidal content the greater the restriction.

(3) Water reaches the subsoil shortly after runoff begins for each storm. After this time, saturation of the topsoil is approached rapidly and transmission and infiltration rates are materially reduced.

(4) Since transmission rates are much lower in the subsoil than in the topsoil little use is made of the available storage space in the subsoil during storms. The greatest differences in soil properties between Muskingum silt loam and Keene silt loam occur in the subsoil. Here the transmission rates are considerably lower in the latter. This is the main reason for greater runoff from Watershed 123 in Keene silt loam.

(5) Frost seems to reduce initial rates of infiltration. The amount and type of frost studied in 1946 did not establish minimum infiltration rates lower than those normally occurring. It is believed that the concrete type of frost may reduce infiltration rates more than the honeycomb type.

(6) Transpiration is an important factor. Starting at the beginning and lasting through much of the period of high-intensity storms, corn plants are small and little transpiration occurs from them while wheat plants are of sufficient growth for considerable transpiration. Due to this transpiration the available storage prior to storms was greater on Watershed 123 in wheat than Waterwhed 103 in corn, and more runoff occured on the latter. A combination of a poorly drained soil and a crop of low transpiration during vulnerable periods is conducive to runoff.

(7) Sealing of the soil surface through the use of crops which expose a considerable area of the soil to the direct impact of raindrops is well known. There was sufficient available storage in the topsoil of all watersheds prior to a few storms to absorb all the rainfall that occurred. The only watershed producing runoff was in corn. Lack of protection of the exposed soil surface when corn is grown has frequently been mentioned.

(8) The subsoil bottleneck is a major consideration as saturation of the topsoil is approached. Whenever it is desirable to have more rainfall of considerable amounts enter the soil it is this bottleneck that must be opened. Whenever feasible, consideration should be given to deep-rooted crops that penetrate the subsoil and to mechanical means of ripping the subsoil.

Needs

These studies emphasize the need for: (1) A coordinated attack by hydrologists, soil scientists, and others, upon the processes involved in infiltration for soils showing important differences in permeability; (2) the assignment of values of transmission-rate ranges to soils; (3) a grouping of soils based on hydrologic characteristics and a grouping of storms based on rainfall characteristics; and (4) relationships between the two groupings mentioned in (3).

It is planned to continue the investigations mentioned herein in such a way as to make necessary assumptions as accurate as possible. Seasonal infiltration curves are being developed for a number of watersheds of slowly permeable and well-drained soils in different land use. These curves will be used as part of the method to separate surface and subsurface flow on larger watersheds and to indicate the supply of water to the soil for the determination of transmission rates. It would seem that information pertaining to such rates would help evaluate the performance of watersheds, the effect of soil properties and conditions, the effect of land use, and runoff, and aid in the solution of other hydrologic problems.

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THE RELATION OF RUNOFF TO PRECIPITATION IN THE SIERRA NEVADA, CALIFORNIA

M. J. Bartell

Abstract--A method is presented for estimating the amount of delayed runoff due to accumulated snow on a drainage area. Although the study as presented pertains to estimating the water supply in the Tuolumne River drainage area, the general principles of the method apply to all Sierra streams. The precipitation-runoff relationship that is discussed forms the practical working tool of the engineer who must efficiently operate reservoirs for the multiple purpose of water supply, power, irrigation, and flood control.

Introduction--Beginning in 1930, the snow surveys of the Division of Water Resources of the State of California have been the basis for estimates of delayed runoff. This information is very valuable to the water-supply studies for all the Sierra Nevada streams; however, the period of the observations is too short for many of the comprehensive studies necessary. This study was undertaken with the idea of supplying information somewhat similar to the snow surveys for the period of stream-flow observations prior to 1930.

The basic principles and data used in the study are: (1) The season for precipitation and stream flow is from October to September, inclusive; (2) The period for determining normals is 1889-1944, or 55 seasons. (3) Fifty-five season normals are calculated for all precipitation stations. Records not covering the entire period were expanded by comparison to Sonora. (4) Stream-flow measurements for the Tuolumne River at La Grange or Modesto are from 1896-1944, or 48 seasons. (5) Stream-flow measurements for sub-divisions of the Tuolumne River Watershed at Hetch Hetchy, Lake Eleanor plus Cherry Creek, are from 1910-1944, or 34 seasons. For the 55 season normals these were expanded by comparison to the total flow at La Grange or Modesto. (6) The word normal as used herein means the 55 season average or mean, calculated or deduced as above noted. The words rainfall and precipitation as used herein are synonymous. (7) Per cents of normal seasonal precipitation as an average or mean for a given area are designated as area per cents or area precipitation.

Runoff--The runoff used is in each case the total water yield of the Watershed for the time passed and area designated, that is, the actual water measurements at a given point are corrected for diversions from the area above that point and for storage withheld or released.

The earlier Tuolumne River water measurements were made near Modesto where the tributary drainage area is 1600 sq mi. Later, the measuring point was moved upstream to a point near La Grange where the tributary drainage area is 1540 sq mi. The difference in area is about four per cent. The 60 sq mi eliminated by moving the gaging station upstream has a normal seasonal precipitation of about 15 inches; the normal seasonal for the entire Watershed is about 45 inches. As a rough estimate 15 inches of precipitation would produce in runoff probably less than one-fifth of that produced by 45 inches. The difference in runoff between the two stations is probably less than one per cent; too small to be considered, and therefore the two records are combined without correction, giving a continuous record for the Tuolumne River from 1896 to the present. This record will hereinafter be referred to as Tuolumne River at La Grange. The relation of runoff to precipitation is based upon the runoff of the Tuolumne River at La Grange. Additional records used for checking or explaining the methods are: Tuolumne River at Hetch Hetchy, Eleanor Creek at Lake Eleanor, Cherry River at Cherry Valley, Merced River at Exchequer, Stanislaus River at Knights Ferry, Yuba River at Smartsville, and the American River at Fair Oaks.

Precipitation--The total precipitation on a given area is the source of the runoff for that area. For comparison to runoff which is given as total acre feet, precipitation must also be expressed as a total quantity such as average depth on area or total acre ft, or a function of the total quantity. Given a sufficient number of precipitation records properly distributed, it would be a simple matter to calculate the total quantity of water contributed by precipitation, but there is not sufficient data for this purpose and other methods must be devised.

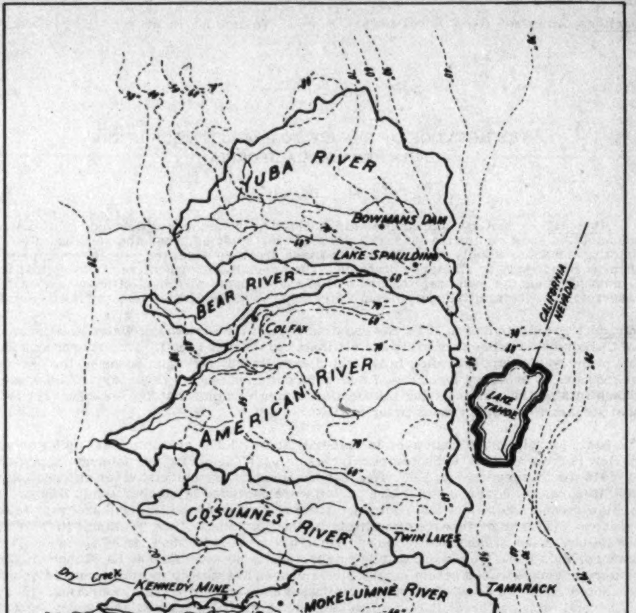
YUBA RIVER
BOWMANS DAM
LAKE SPAULDING
BEAR RIVER
COLFAX
CALIFORNIA
NEVADA
LAKE TAHOE
AMERICAN RIVER
COSUMNES RIVER
TWIN LAKES
Dry Creek
KENNEDY MINE
MOKELUMNE RIVER
TAMARACK
WEST POINT
CALAVERAS RIVER
STANISLAUS RIVER
SONORA
TUOLUMNE RIVER
LAKE ELEANOR
HETCH HETCHY
SEQUOIA
MERCED RIVER
YOSEMITE
SUMMERDALE
60"
70"
50"
40"
Scale
0 5 10 15 20 25 Miles

Fig. 1--Isohyetes and drainage basins of the Sierra Nevada, California for the region from Yuba River to Merced River, inclusive

As will be shown later, precipitation over the Sierra, with certain well-known limitations, is quite closely related, so that data from the entire area can be used in calculating the detail of any particular area. The comparison of precipitation records is made on the basis of their normals.

For each precipitation station (see Fig. 1) the 55 season normal in inches is taken as 100 per cent and each season is calculated as a per cent of the 55 season normal, thus facilitating direct comparison of precipitation, station to station, regardless of their relative intensities which vary from about 15 to 75 inches.

Before describing the procedure it is necessary to mention some of the characteristics of the precipitation of the Sierra Nevada. (1) From West to East, up the Sierra slope, rainfall increases with elevation up to about 5000 ft and then decreases. The rates of increase and decrease are fairly uniform. Across the Tuolumne River Area, starting at the toe of the west slope of the Sierra in the San Joaquin Valley, the normal precipitation is about 15 inches and from this point up the slope the precipitation increases to a maximum of about 55 inches at elevation 5000 ft, then gradually decreases to about ten inches at the foot of the eastern slope. Likewise across the Feather River area, the increase is from about 20 inches to a maximum of nearly 80 inches from which it decreases to about 20 inches at the toe or foot of the eastern slope. (2) From the foregoing it will be noted that along the axis of the Sierra normal precipitation increases from south to north. The rate of increase, south to north, like the variation east to west, is also quite uniform, as shown by the many comparisons given later. (3) Considering the variation in intensity just described under the headings (1) and (2) when the precipitation is say 110 per cent of normal on the Merced River Area it is also 110 per cent on the Feather River Area (just north of the Yuba River Area) and all the area in between. Seasonally there are exceptions to this uniform distribution. The precipitation is fairly uniform in about 25 of the 48 seasons 1896-1897 to 1943-1944. For the remaining 23 seasons there is a deviation from uniform distribution of precipitation, particularly from south to north along the axis of the Sierra, an example of which is shown in Table 1.

Table 1--Per cent of normal precipitation

Season	Tuolumne River area	Yuba River
	pct	pct
1903-1904	117	145
1905-1906	153	133
1906-1907	156	155
1910-1911	147	130

The deviation from the uniform seasonal distribution is gradual and presents no particular difficulty in evaluating the seasonal per cent of normal for any particular area. The entire study is based upon the 55 season normals and the seasonal relation thereto. It must be presumed, therefore, that any and all variations in the seasonal relations between precipitation stations are compensating.

Occasionally stations will show precipitation entirely out of line with all the other stations being considered, caused most probably by extremely intense local storms over limited areas. Some of the records may be erratic. In the few cases encountered no special check was made to discover the cause of deviation. If the record is correct some weight should of course be given, but the number of precipitation records in any area is entirely too small to permit a proper evaluation, so there remained only the expedient of discarding such erratic records for the period or season under consideration.

Analysis of data--With the information as to the variations in the distribution of the precipitation just presented we are ready for the first step of the study and that is to establish the relation of runoff to precipitation.

As previously stated, runoff is given as a volume and therefore for comparison, precipitation must also be expressed as a volume. Precipitation can be expressed as a volume for the Tuolumne River tributary to La Grange, as follows:

From a previous study it was determined that the normal precipitation for the entire Tuolumne River Area, 1540 sq mi, is 45 inches of water on the area. Then the volume of precipitation in ac ft for any season is $640 \times 1540 \times 45 \times$ seasonal per cent/12 = ac ft on the Tuolumne Area.

The area per cent for each season, is the function which varies with the runoff and therefore is the only factor necessary in determining the relation of runoff to precipitation. The most convenient form of expressing the relation is shown on Figure 2.

The normal precipitation for 13 stations in the Sierras as shown on Figure 1 were calculated for the 55 seasons, 1889-1944. Where the observed record did not cover the entire period for a station, the normal precipitation was expanded by comparison to Sonora which has a 55-year record.

Table 2--Seasonal rainfall as a per cent of normal rainfall (October to September),

Item or year (ending Sept. 30)	Sonora 1	Hetch Hetchy 2	Lake Eleanor 3	Sequoia 4	Tamarack 5	Twin Lakes 6	Summerdale 7	Mean 1-7
Elevation (ft)	1825	3530	4650	4452	8000	7970	5270	...
Average precipitation (inches)	33.06[a]	35.97	44.45	52.10	48.50	45.75	52.75	...
1890	209	...	...	...	...	...	...	209
1891	94	...	...	...	...	...	...	94
1892	92	...	...	...	...	...	...	92
1893	133	...	...	...	...	...	...	133
1894	116	...	...	...	...	...	...	116
1895	137	...	...	...	...	...	...	137
1896	93	...	...	...	...	...	...	93
1897	115	...	...	122	...	...	99	112
1898	66	...	...	62	...	...	59	62
1899	97	...	...	78	...	...	72	82
1900	101	...	...	94	75[b]	...	95	97
1901	148	...	...	149	124	...	167[b]	140
1902	79	...	...	87	87	...	81	84
1903	100	...	...	107	...	...	94	100
1904	114	...	...	117	...	...	111	114
1905	90	...	...	83	...	...	79	84
1906	155	...	...	159	...	...	160	158
1907	150	...	...	128	194	...	136	152
1908	62	...	...	63	79	...	82	72
1909	108	...	...	115	111	...	124	115
1910	93	...	...	112	106	...	100	103
1911	128	131	129	...	173	...	152	143
1912	63	69	61	...	72	...	58	65
1913	52	68	58	...	94	...	...	68
1914	116	127	124	...	106	...	...	118
1915	114	78	98	...	76	...	...	92
1916	114	86	98	...	105	...	...	101
1917	93	86	97	...	87	...	...	91
1918	80	79	80	...	73	...	...	78
1919	56	77	75	...	73	...	...	70
1920	96	78	67	...	69	89	...	80
1921	93	109	89	...	109	140[b]	...	100
1922	102	87	83	...	94	...	...	92
1923	93	90	95	...	102	93	...	93
1924	38	41	41	...	52	43	...	43
1925	109	125	110	...	79	99	...	104
1926	71	74	71	...	43[b]	61	...	69
1927	103	105	103	...	75[b]	95	...	101
1928	90	100	99	...	...	63	...	88
1929	72	75	66	...	...	84	...	74

(Continued)

1889-1944; for use as an index of the average rainfall for the Tuolumne River Watershed

Yosemite	West Point	Kennedy Mine	Colfax	Lake Spaulding	Bowmans Dam	Mean 8-13	Rainfall per cent of normal × 45	Selected mean for Watershed
8	9	10	11	12	13		in	
3983	2736	1500	2418	4600	5347	...	...	...
36.56	40.69	30.89	48.19	68.31	70.73	...	...	...
						...	...	...
....	...	...	192	...	195	193	81.0	180
....	...	...	79	...	87	83	36.0	80
....	...	...	94	...	78	86	41.3	92
....	...	143	110	...	...	126	37.5	128
....	...	144	112	...	...	128	49.5	110
....	149	176[b]	133	130	148	139	63.0	140
....	98	117	134	126	130	121	52.7	117
....	112	149	104	109	117	118	51.7	115
....	58	72	67	60	58	63	27.9	62
....	83	93	94	87	92	90	36.9	82
....	98	121	133	107	114	114	43.6	97
....	140	147	140	123	116	132	61.2	136
....	83	110[b]	98	92	87	90	39.1	87
....	108	140[b]	102	94	108	103	45.0	100
....	142	131	160	159	209[b]	148	54.0	120
81	82	99	91	88	120[b]	88	38.7	86
145	141	121	143	138	120	134	68.8	153
152	143	148	137	146	129	142	70.2	156
61	57	63	68	75	69	65	30.6	68
133	113	107	122	138	132	124	55.3	123
121	101	99	105	109	100	106	46.3	103
103	138	120	125	115	...	120	65.7	145
57	69	68	64	66	...	65	29.2	65
71	63	48	45	64	74	61	30.6	68
102	120	101	108	125	88[b]	110	54.0	120
103	108	91	111	86	96	99	45.0	100
95	105	95	110	108	...	102	46.8	104
97	87	69	98	90	...	89	40.9	91
82	86	85	76	69	...	79	36.0	80
64	71	76	81	89	...	76	32.8	73
69	74	68	66	69	...	69	35.5	79
84	113	102	108	109	...	103	45.0	100
91	95	89	107	111	...	98	47.7	106
93	106	117	98	93	...	101	42.7	95
35	36	37	38	44	...	38	19.3	43
110	105	109	96	103	...	104	45.9	102
77	70	65	78	71	64	71	31.5	70
113	114	97	116	119	94	109	45.4	101
87	97	83	84	91	79	86	39.1	87
75	78	69	61	61	54	66	31.5	70

(Continued)

Table 2--Seasonal rainfall as a per cent of normal rainfall (October to September).

Item or year (ending Sept. 30)	Sonora 1	Hetch Hetchy 2	Lake Eleanor 3	Sequoia 4	Tamarack 5	Twin Lakes 6	Summerdale 7	Mean 1-7
Elevation (ft)	1825	3530	4650	4452	8000	7970	5270	. . .
Average precipitation (inches)	33.06[a]	35.97	44.45	52.10	48.50	45.75	52.75	. . .
1930	72	75	74	. . .	. . .	103[b]	. . .	74
1931	56	59	63	. . .	. . .	61	. . .	60
1932	102	107	118	. . .	. . .	81	. . .	102
1933	62	59	72	. . .	. . .	71	. . .	66
1934	71	66	67	. . .	. . .	58	. . .	65
1935	115	114	121	. . .	. . .	87	. . .	110
1936	125	108	109	. . .	. . .	120	. . .	115
1937	112	101	101	. . .	. . .	99	. . .	103
1938	146	157	147	. . .	. . .	169	. . .	154
1939	73	76	73	. . .	. . .	77	. . .	75
1940	113	108	115	. . .	. . .	108	. . .	111
1941	119	122	124	. . .	. . .	112	. . .	119
1942	109	116	117	. . .	. . .	120	. . .	115
1943	112	113	121	. . .	. . .	114	. . .	115
1944	80	82	83	. . .	. . .	. . .	. . .	82

[a] 55 years [b] Not included in means

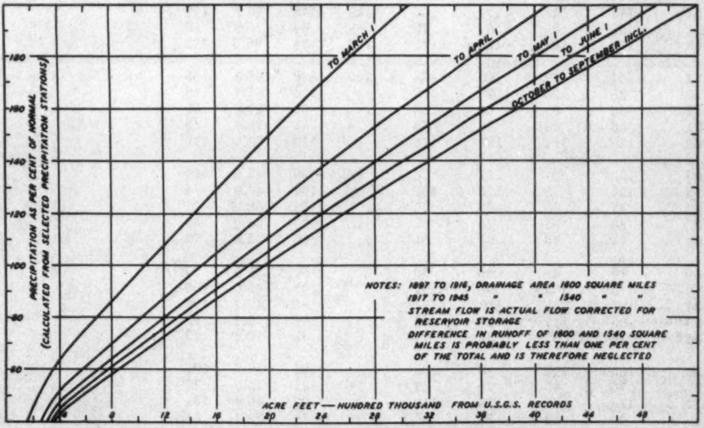

Fig. 2--Tuolumne River at La Grange showing relation of precipitation to potential runoff; stream flow plus delayed runoff, October to March; October to April 1; October to June 1; and October to September

1889-1944; for use as an index of the average rainfall for the Tuolumne River Watershed

Yosemite	West Point	Kennedy Mine	Colfax	Lake Spaulding	Bowmans Dam	Mean 8-13	Rainfall per cent of number × 45	Selected mean for Watershed
8	9	10	11	12	13		in	
3983	2736	1500	2418	4600	5347	...	...	...
36.56	40.69	30.89	48.19	68.31	70.73	...	...	...
71	73	67	82	79	81	75	32.8	73
54	55	54	50	61	58	55	25.2	56
110	95	89	94	98	91	97	46.3	103
69	60	65	48	60	66	62	29.7	66
63	75	73	73	69	70	69	29.2	65
118	106	95	97	98	96	101	45.9	102
113	125	126	123	112	122	119	51.7	115
106	95	99	100	74	85	93	46.3	103
167	135	112	134	121	163	139	66.6	148
66	62	63	56	60	72	63	29.7	66
111	114	97	107	129	123	113	49.9	111
125	108	92	129	128	106	116	53.5	119
132	116	113	126	127	108	121	51.7	115
120	122	120	112	117	108	115	51.7	115
81	74	70	81	72	...	76	35.5	79

Having the 55 season normals, the seasonal precipitation for each station was divided by its normal and recorded as a per cent of normal. These data are summarized as shown in Table 1 to facilitate the calculation of the average per cent of normal for the Tuolumne River Watershed.

The selection of the precipitation stations, and their arrangement in Table 2, were made in view of the actual and probable variations of the seasonal precipitation previously discussed. At the bottom of the table is given for each season the selected mean for Watershed. The term selected indicates that no rigid rule was followed in arriving at the mean, that is, for each season proper allowance was made for any variation of precipitation along the axis of the Sierra. In general, if the variation south to north was too great only the Tuolumne stations were used, otherwise all of the stations were used.

With the seasonal mean per cents of precipitation, Table 2, and the seasonal runoff, the curve showing the relation of precipitation to runoff is constructed as shown on Figure 2. In general, the several points as plotted are in fairly close agreement and it is thought that the curve is quite accurate; also the irregular pattern of the occurrence of the precipitation during any season is such that no part of the season's precipitation can be taken as a reliable index to what will follow. The first two-thirds (to March 1) of the precipitation may be 50 per cent of normal and the later one-third (March 1 to September 30) almost three times as much or vice versa, as shown in Table 3.

A study of the plotted points from which the runoff curve was made (see Fig. 2) shows that the irregularity of the seasonal precipitation has no apparent influence in its relation to runoff; that is, the relation of precipitation to runoff is entirely independent of the manner of the occurrence of the precipitation for the extent of the relations shown on Figure 2. It follows, therefore, that the relation also applies to the accumulated precipitation during the season, beginning from the lowest precipitation shown on the curve.

Table 4--Seasonal normal precipitation to given dates and

No.	Station or item	Through February				Through March			
		Normal		1928-1929		Normal		1928-1929	
		in	pct	in	pct	in	pct	in	pct
1	Sonora	22.64	68.4	17.79	79	28.24	85.4	26.90	95
2	Hetch Hetchy	23.01	64.0	20.12	87	28.78	80.0	31.06	104
3	Lake Eleanor	29.76	67.0	24.10	81	36.62	82.4	38.25	104
4	Sequoia	35.17	67.5	....	82	44.95	86.2	....	101
5	Tamarack	31.86	65.7	....	..	38.90	80.3	....	...
6	Twin Lakes	30.57	66.9	18.56	61	37.33	81.7	24.50	66
7	Summerdale	36.12	68.4	....	..	45.45	86.1	....	...
	Average 1-7	....	66.8	....	77	....	83.2	....	92
	Precipitation to stream flow	....	...	....	87	....	...	....	103
8	Yosemite	24.37	66.7	17.39	71	30.17	82.5	27.19	90
9	West Point	27.47	67.5	21.67	79	34.08	83.8	35.52	101
10	Kennedy Mine	21.07	68.2	15.09	72	25.97	84.1	22.94	88
11	Colfax	33.30	69.1	21.74	65	40.72	84.5	36.81	90
12	Lake Spaulding	46.32	67.6	31.87	69	56.86	83.0	55.82	98
13	Bowmans Dam	47.26	66.8	27.37	58	59.21	83.7	49.11	83
	Average 8-13	....	67.7	....	69	....	83.6	....	92
14	Tuolumne Watershed	30.24	67.2	....	..	37.53	83.4	....	...
15	Selected per cent of normal	....	...	....	73	....	...	....	92
16	Total runoff, Curve 1, ac ft	....	...	560,000		....	...	1,290,000	
17	Stream flow ac ft	....	...	280,000		....	...	623,000	
18	Delayed runoff	....	...	280,000		....	...	667,000	

Table 3--Tuolumne Area precipitation

Season	To March 1	March 1 to September 30
	pct	pct
1908-1909	162	69
1913-1914	152	64
1905-1906	107	245
1911-1912	40	125

Midseason-runoff estimates--Midseason-runoff estimates made on the basis of accumulated precipitation gives data of great value for use in conservation and flood-control studies. For this purpose the season is divided into five periods and the precipitation normals are calculated for each of the periods as illustrated in Table 4. The procedure for deriving the area per cents for the part season periods, is the same as that already described for the season as shown in Table 2.

Opposite each period normal is given, as a per cent, its relation to the normal for the entire season. In line 14 is given the average per cent of all the stations for the period and the average precipitation on the area in inches determined by multiplying per cent by 45. For example, the average per cent of the column for February 28-29 is 67.2 which times 45 gives 30.24 inches as shown.

The most convenient method of calculating the total runoff is by use of selected per cent (line 15) and the period post-season curves (see Fig. 2). The vertical scale relation in each case is the ratio of the period normals divided by the seasonal normals as shown in line 14 (see Table 4). For the vertical scale the March 1 curve is in all cases 67.2 per cent of the season curve; the curve April 1 is likewise 83.4 per cent of the seasonal curve, and so on. With the selected per cent line 15, (see Table 4), the runoff can be read directly from the period curves thus saving in each case an intermediate calculation.

The total runoff (see Table 4, line 16) is the actual runoff to be anticipated from the precipitation to the date given, and this total runoff, less the stream flow to date, line 17, gives the delayed runoff, line 18. The delayed runoff, as previously noted, is the additional runoff to be expected from the precipitation that has occurred to the date given. The successive calculations of the delayed runoff for the periods to March 1, April 1, May 1, and June 1, are the final object of this study and the value of this advance information to flood control and conservation studies is obvious.

precipitation season calculated as per cent of normal, Tuolumne River Area

Through April				Through May				Season			
Normal		1928-1929		Normal		1928-1929		Normal		1928-1929	
in	pct	in	pct	in	pct	in	pct	in	pct	in	pct
30.93	93.5	29.19	95	32.32	97.7	29.52	91	33.08	100	29.65	90
32.02	89.1	34.19	106	34.09	94.8	35.10	100	35.96	100	36.02	100
40.34	90.8	42.11	104	42.53	95.7	42.93	101	44.45	100	43.85	99
48.84	93.7	....	102	50.77	97.4	....	97	52.13	100	....	96
42.00	86.7	....	...	44.47	91.8	....	...	48.46	100	....	...
40.48	88.6	28.50	70	42.66	93.3	29.00	68	45.71	100	29.05	63
49.59	94.0	....	...	51.43	97.5	....	...	52.78	100	....	...
....	90.9	....	94	....	95.5	....	90	....	...	....	88
....	...	....	100	....	...	....	98	....	...	....	85
32.91	90.1	30.26	92	34.64	94.8	31.39	91	36.55	100	31.84	87
37.46	92.1	39.05	104	39.30	96.6	39.16	100	40.69	100	39.46	97
28.54	92.4	25.30	88	29.88	96.7	25.33	85	30.89	100	25.73	83
44.48	92.3	40.32	91	46.70	96.9	40.32	86	48.19	100	40.50	84
62.19	90.7	61.17	98	65.84	96.1	61.68	94	68.53	100	62.50	91
64.32	90.9	54.86	85	67.91	96.0	55.43	82	70.74	100	56.05	79
....	91.4	....	93	....	96.2	....	90	....	...	....	86
41.00	91.1	....	...	43.11	95.8	....	...	45.00	100	....	...
....	...	....	94	....	...	....	90	....	...	....	87
....	...	1,540,000		....	...	1,550,000		....	...	1,580,000	
....	...	887,000		....	...	1,335,000		....	...	1,525,000	
....	...	653,000		....	...	215,000		....	...	....	

Summary--The foregoing study shows only one of the uses of the relation of precipitation to runoff for conservation or flood-control studies. The snow surveys give information necessary for the intelligent operation of all Sierra reservoirs, and the present service though excellent, should be expanded. The average seasonal snow storage of the Sierra produces from 15 to 20 million ac ft of water, making this one of the largest storage areas in the world.

There are many possibilities for the expansion of the general method and its application to the sub-divisions of each watershed as a help to the snow-survey work; but the most urgent need now is for more precipitation records, particularly in the snow-field area. The conical snow gage devised by the United States Weather Bureau for the United States Engineers is a start in this direction.

It is the intention to install such gages on the Tuolumne River Area. There is also urgent need for the expansion of the snow surveys of the State Division of Water Resources for the entire Sierra Area. For the Tuolumne Area the snow-survey facilities are being expanded. Five snow-survey cabins have been built and additional snow-measurement courses added during 1947. Additional facilities are planned.

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A REFERENCE PLANE OF FLOOD VOLUMES IN THE SACRAMENTO-SAN JOAQUIN BASIN, CALIFORNIA

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Abstract--A need exists for a reliable method of establishing a reference plane of flood runoff for comparison of degree of protection provided by flood-control projects. This paper presents a method of establishing such a reference plane for the Sacramento-San Joaquin Basin based on a statistical study of the flood runoff which has been recorded in California and the correlation of flood runoff with various stream-basin characteristics.

The study presented in this paper was undertaken for the purpose of establishing a reference plane of flood runoff that would be equally applicable to all streams in the Sacramento-San Joaquin Basin of California. This reference plane of flood-runoff volumes was intended to represent a flood that would be exceeded in magnitude only on relatively rare occasions. Examination of runoff records of streams in California reveals that a great variation exists in the amount of flood runoff that occurs, even on streams fairly close together, when expressed in terms of inches of depth on the stream basin. A similar variation occurs in the depth of runoff for which space has been provided or for which space is proposed in reservoirs for flood-control purposes. In 1943, engineers responsible for reviewing flood-control reports pertaining to the Sacramento-San Joaquin Basin called attention to the need for a method of answering the question: Was the protection provided by setting aside space in a reservoir on a certain stream sufficient to store two inches of runoff comparable with that provided by the storage of five inches of runoff on some other stream?

In an attempt to answer this question, a statistical study of flood volumes was made in the fall of 1943, based on the recorded runoff from 46 streams and utilizing two parameters (annual precipitation and size of stream basin) and was only partially successful. In 1947 a second and much more comprehensive study was made for the same purpose. This second study is essentially the one presented in this paper.

A study of an annual precipitation map for California indicates that much of the variation in the depth of flood runoff that has been recorded is undoubtedly due to location and topography, as the amount of precipitation and the form in which it falls varies greatly in different parts of California. This variation is apparently due partly to (1) the peculiarities of the global circulation of the atmosphere over the State which extends from latitude 32°.5 near the horse latitude (a region of calm) to latitude 42°, in the so-called polar front (a region of great storm activities), and (2) the many high mountain ranges in the State. Some areas are desert-like with an annual precipitation of five inches or less; other areas have an annual precipitation of over 100 inches. On the high mountain ranges, great depths of snow accumulate during the winter season giving rise to large summer snow-melt floods. Due principally to the mountainous topography, precipitation is predominantly orographic in nature and follows a rather definite pattern controlled by the location of the mountain ranges and mountain passes. Figure 1, a map of California, shows the location of the principal mountain ranges and streams.

The Sacramento-San Joaquin Basin, which occupies the central portion of the State, contains an area of relatively level valley floor about 450 mi long and about 50 mi wide, separated from the Pacific Ocean and enclosed on all sides by fairly continuous mountain ranges. On the south, the basin is bounded by the Tehachapi Mountains, which vary from 5000 to 7000 ft in elevation; on the west by the Coast Ranges, which vary from about 2000 to 7000 ft in elevation; with comparatively low elevations near San Juis Obispo, Monterey, and San Francisco; on the north by the Klamath Mountains which vary from about 7000 to 9000 ft in elevation; and on the east by the Cascade Mountains and the Sierra Nevada, which vary from about 6000 to 14,000 ft in elevation, with the highest elevation in the south at Mt. Whitney.

Two entirely different approaches to the problem of establishing the desired reference plane of flood volume for the Sacramento-San Joaquin Basin are possible; one, based on precipitation in which historical storms that have occurred in or adjacent to the Sacramento-San Joaquin Basin are

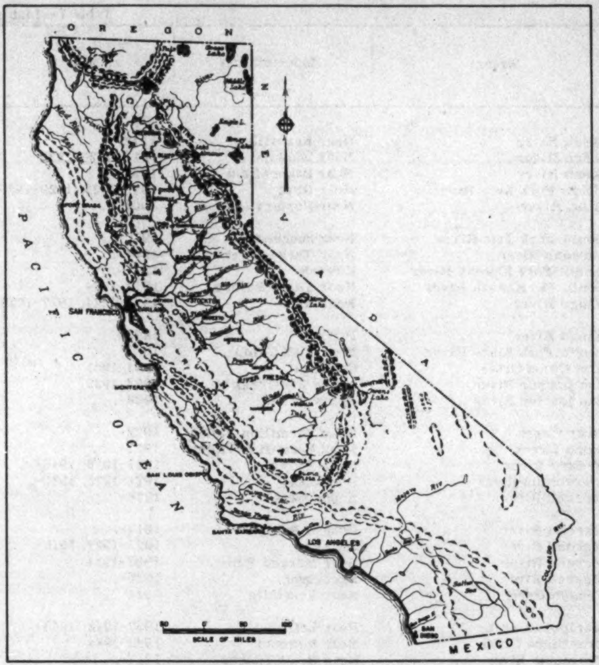

Fig. 1--Map of California

transposed so as to center artificially exactly over a selected watershed, and then computing a hydrograph of runoff by some means such as the unit hydrograph method; the other approach would be to study the volume of flood runoff which has been actually recorded on streams within and adjacent to the Sacramento-San Joaquin Basin and to develop correlations between the depth of runoff and various indices, such as wetness and topographic features. Each of the approaches has certain advantages and disadvantages, but for the Sacramento-San Joaquin Basin, the runoff approach is considered to be much the better for reasons to be discussed later, and is the method presented in this paper.

Runoff data from 148 stream gaging stations were used in this study. These stations, all but one of which are located in California, were selected as representative of a wide range of geographic topographic conditions. Six of the runoff records were for a period of over 50 years in length and 24 others for over 40 years, all of which represent the longest periods of record on streams in western United States. Considerable of the runoff data available were affected by diversions for irrigation or power or by reservoir storage. Such flows were corrected for the larger diversions and storages so as to represent natural conditions. Corrections were usually not attempted for minor diversions and storages, as in most instances the necessary data were not available. The runoff records collected by the United States Geological Survey were the source of the greater portion of the runoff data, with some being secured from other governmental agencies and private interests. Topographical data used were taken from the United States Geological Survey quadrangle maps and from aeronautics charts published by the United States Coast and Geodetic Survey.

Table 1--List of streams

No.	Stream	Index station	Year	Annual runoff
				in
1	Kern River	Near Kernville	1912-. . .	12.4
2	Kern River	Near Isabella	1911, 1926-1935	11.8
3	Kern River	Near Bakersfield	1893-. . .	6.0
4	South Fork Kern River	Near Onyx	1912-1925, 1929-1939	3.7
5	Tule River	Near Porterville	1901-. . .	7.9
6	South Fork Tule River	Near Success	1930-. . .	6.1
7	Kaweah River	Near Three Rivers	1904-. . .	15.1
8	North Fork Kaweah River	Kaweah	1911-. . .	12.1
9	South Fk. Kaweah River	Near Three Rivers	1912-1924	15.4
10	Kings River	Near Hume	1922-1924, 1927-1936	23.3
11	Kings River	Piedra	1895-. . .	19.1
12	North Fork Kings River	Near Cliff Camp	1922-. . .	26.8
13	Los Gatos Creek	Coalinga	1931-1941	1.1
14	San Joaquin River	Above Big Creek	1923-1939	27.2
15	San Joaquin River	Below Friant	1908-. . .	21.0
16	Bear Creek	Near Vermilion Valley	1922-. . .	25.1
17	Mono Creek	Near Vermilion Valley	1922-. . .	26.1
18	Fresno River	Near Knowles	1911-1913, 1915-. . .	8.7
19	Chowchilla River	Buchanan	1921-1923, 1930-. . .	5.9
20	Merced River	Happy Isles	1916-. . .	27.9
21	Merced River	Pohono Bridge	1917-. . .	28.2
22	Merced River	Kittridge	1923-1927, 1930-. . .	19.5
23	Merced River	Near Merced Falls	1902-1914	18.6
24	Merced River	Exchequer	1915-. . .	18.6
25	Tenaya Creek	Near Yosemite	1914-. . .	32.3
26	Mariposa Creek	Near LeGrand	1937-1942, 1945-. . .	3.8
27	Orestimba Creek	Near Newman	1932-1944	2.1
28	Tuolumne River	Near Hetch Hetchy	1911-. . .	32.3
29	Tuolumne River	Near LaGrange	1897-. . .	22.5
30	Falls Creek	Near Hetch Hetchy	1916-. . .	47.0
31	Cherry Creek	Near Hetch Hetchy	1911-. . .	48.7
32	Eleanor Creek	Near Hetch Hetchy	1910-. . .	40.8
33	South Fork Tuolumne River	Near Oakland Rec. Cp.	1924-. . .	16.2
34	M. Fork Tuolumne River	Near Oakland Rec. Cp.	1917-. . .	15.7
35	Woods Creek	Near Jacksonville	1926-. . .	9.6
36	M. Fork Stanislaus River	Near Sand Bar Flat	1905-. . .	29.6
37	North Fork Stanislaus River	Near Avery	1915-1922, 1929-. . .	33.4
38	Stanislaus River	Below Melones P. H.	1931-. . .	24.2
39	Stanislaus River	Near Knights Ferry	1904-1915, 1916-1932	22.1
40	Calaveras River	Jenny Lind	1907-. . .	9.7
41	Cosgrove Creek	Near Valley Springs	1930-. . .	7.0
42	Bear Creek	Near Lockeford	1930-. . .	3.7
43	North Fork Mokelumne River	Below Salt Spring Dam	1927-. . .	42.3
44	Mokelumne River	Near Mokelumne Hill	1928-. . .	26.4
45	Mokelumne River	Near Clements	1905-. . .	23.4
46	Cold Creek	Near Mokelumne Peak	1928-1942, 1943-. . .	40.4
47	Bear River	Pardoe Camp	1928-. . .	50.7
48	Sutter Creek	Near Sutter Creek	1923-1936, 1936-1940	11.2

and basic data

Mean elevation	Area stream basin	Orientation	Maximum recorded depth of runoff								
			Duration in days								
			Winter rain					Summer snow-melt			
			1	3	5	20	40	5	30	60	120
ft	sq mi	°	in	in	in	in	in	in	in	in	in
8200	845	0	0.26	0.57	0.75	2.4	3.6	1.4	6.4	10.7	17.6
7900	1070	0	0.20	0.34	0.43	1.1	1.7	0.59	3.1	5.3	8.0
6400	2420	30	0.24	0.51	0.63	1.7	2.6	...	...	...	...
7800	531	6	0.12	0.24	0.30	0.65	1.0	0.67	2.9	4.5	5.6
4000	266	63	1.1	2.2	2.6	5.2	5.8	1.6	4.7	8.8	13.6
3650	106	100	1.4	2.9	3.5	7.2	9.1	0.70	2.3	5.7	7.1
5900	520	53	0.93	1.6	1.9	4.5	5.9	2.2	10.0	17.6	28.8
4900	128	109	1.6	2.7	3.0	5.4	8.1	1.4	6.2	11.6	15.3
5200	73	112	0.96	1.6	1.8	3.8	5.5	...	...	...	...
9400	838	80	0.13	0.26	0.42	1.3	1.9	...	...	...	...
7800	1694	75	0.83	1.4	1.8	3.1	4.0	2.7	11.3	24.6	32.8
9100	174	28	1.4	1.7	1.9	2.8	3.1	5.5[a]	23.6[a]	39.4[a]	51.6[a]
2420	105	60	0.41	0.64	0.79	1.6	2.6	...	...	...	...
8500	1042	40	1.2	1.6	1.8	2.2	2.4	...	...	...	...
7300	1675	47	0.86	2.0	2.4	3.7	5.1	2.3	10.7	18.3	28.3
10850	54	90	0.17	0.28	0.36	0.67	1.2	3.1	14.2	25.2	36.1
9950	92	56	0.08	0.18	0.26	0.61	1.1	3.0	14.0	23.8	33.6
3000	132	28	1.3	2.4	3.0	8.1	12.3	0.71	3.3	5.6	8.5
1900	238	35	1.4	2.3	3.0	7.8	11.8	...	...	...	...
9300	181	104	1.1	1.7	1.9	2.4	2.7	...	...	...	...
8450	321	89	1.9	2.9	3.4	4.1	4.6	4.2	19.5	30.5	40.0
6000	935	87	1.3	2.0	2.3	4.8	7.9	...	...	...	...
5200	1048	74	1.3	3.0	3.5	5.4	6.8	...	...	...	...
5300	1035	77	1.3	3.1	3.5	5.1	6.8	...	...	...	...
8800	47	42	2.7	4.2	4.8	5.7	6.2	4.3	18.6	31.9	41.3
2000	116	45	1.2	2.4	2.9	5.4	9.2	...	...	...	...
1500	129	95	0.51	0.7	0.8	2.8	4.8	...	...	...	...
9100	462	84	2.1	2.8	3.0	3.7	4.2	4.3	19.6	32.0	42.2
5900	1540	60	1.2	3.1	3.7	7.2	9.1	2.1	9.5	17.7	23.2
8450	45	40	3.3	6.0	6.7	7.7	8.5	...	...	...	...
8000	111	36	3.9	7.8	8.6	9.8	10.8	...	...	...	...
7250	74	48	5.3[a]	9.6[a]	10.2[a]	11.2	11.9	...	...	...	...
5500	88	98	1.7	2.8	3.2	5.9	8.5	1.8	9.4	16.7	22.9
6700	71	84	0.78	1.3	1.5	3.2	4.9	...	...	...	...
2150	98	30	2.7	5.0	5.6	8.7	11.1	...	...	...	...
7400	318	60	2.1	3.3	3.6	4.6	5.3	3.5	17.1	26.0	41.4
7000	163	53	2.9	4.5	4.9	5.5	6.4	5.7	31.6	45.0	47.9
6000	898	52	0.86	1.6	2.6	4.7	7.5	...	...	...	...
5600	982	52	2.2	4.4	5.7	10.3	13.3	2.4	11.2	19.6	31.2
1700	395	67	2.4	5.0	5.5	11.6	13.3	...	...	...	...
1280	21	15	1.9	3.5	3.9	9.6	10.7	...	...	...	...
300	48	80	1.1	2.1	2.5	5.8	6.2	...	...	...	...
8000	160	70	3.8	6.3	6.9	8.2	9.0	3.5	15.3	24.2	35.9
5500	538	65	1.9	3.4	4.2	6.3	7.1	...	...	...	...
5500	630	67	1.6	3.2	4.3	8.6	11.0	2.4	10.8	18.5	30.2
7000	23	30	3.9	7.0	7.3	9.1	13.0	...	...	...	...
6600	33	51	4.4	6.8	8.3	10.9	13.1	6.3	30.2	44.1	52.6
2500	53	66	1.9	3.8	4.6	6.1	6.5	...	...	...	...

(Continued)

Table 1--List of streams

No.	Stream	Index station	Year	Annual runoff
				in
49	M. Fork Mokelumne River	West Point	1912-. . .	12.7
50	Cosumnes River	Michigan Bar	1908-. . .	12.9
51	North Fork Cosumnes River	Near El Dorado	1911-1939	15.7
52	Rock Creek	Near Farmington	1940-. . .	4.1
53	Duck Creek	Near Farmington	1940-. . .	2.5
54	Littlejohn Creek	Near Eugene	1940-. . .	3.7
55	Littlejohn Creek	Farmington	1940, 1945-. . .	3.8
56	Fine Gold Creek	Near Friant	1937-. . .	8.1
57	Dry Creek	Near Dustin Road	1943-. . .	4.3
58	Sacramento River	Antler	1912-1939	36.6
59	Sacramento River	Near Red Bluff	1895-. . .	16.8
60	Local Sacramento River	Kennett-Red Bluff	1896-. . .	18.0
61	Local Sacramento River	Kennett-Big Bend	1925-1940	40.8
62	Local Sacramento River	Red Bluff-Chico Lnd.	1925-1940	6.8
63	Pit River	Fall River Mills	1921-. . .	1.7
64	Pit River	Big Bend	1910-. . .	7.7
65	McCloud River	Baird	1911-1939	39.7
66	Clear Creek	Near Igo	1941-. . .	26.6
67	Cottonwood Creek	Near Cottonwood	1941-. . .	13.1
68	Battle Creek	Near Cottonwood	1941-. . .	19.3
69	Antelope Creek	Near Red Bluff	1941-. . .	17.4
70	Mill Creek	Near Los Molinos	1910-1913, 1928-. . .	25.2
71	Thomes Creek	Paskenta	1921-. . .	19.1
72	Deer Creek	Near Vina	1912-1915, 1920-. . .	20.1
73	Chico Creek	Near Chico	1930-. . .	30.0
74	Butte Creek	Near Chico	1931-. . .	37.6
75	Elder Creek	Near Henleyville	1931-1941	10.5
76	North Fork Feather River	Big Bar	1911-1930, 1932-. . .	21.9
77	Feather River	Near Oroville	1902-1934, 1934-. . .	23.9
78	Butt Creek	Near Butte Valley	1906-1910, 1912-1920	14.7
79	Indian Creek	Near Crescent Mills	1906-1918, 1930-. . .	10.0
80	Spanish Creek	Keddie	1912-. . .	18.0
81	West Branch Feather River	Near Yankee Hill	1931-. . .	42.7
82	M. Fork Feather River	Near Clio	1926-. . .	6.5
83	M. Fork Feather River	Sloat	1912-1927	9.7
84	M. Fork Feather River	Bidwell Bar	1912-. . .	21.4
85	South Fork Feather River	Enterprise	1913-. . .	39.7
86	M. Fork Yuba River	Milton	1926-. . .	39.0
87	M. Fork Yuba River	North San Juan	1912-1941	33.5
88	Yuba River	Near Smartville	1904-. . .	37.6
89	Oregon Creek	Near North San Juan	1912-. . .	29.5
90	North Fork Yuba River	Near Sierra City	1924-. . .	37.4
91	North Fork Yuba River	Below Goodyears Bar	1911-1931	43.0
92	North Fork of Yuba River	Downieville	1911-1926	46.8
93	Rock Creek	Goodyears Bar	1911-1933	37.8
94	Goodyears Creek	Goodyears Bar	1911-1933	48.5
95	Deer Creek	Near Smartville	1936-. . .	26.6

and basic data (Continued)

Mean elevation	Area stream basin	Orientation	Maximum recorded depth of runoff								
			Duration in days								
			Winter rain					Summer snow-melt			
			1	3	5	20	40	5	30	60	120
ft	sq mi	°	in	im	in	in	in	in	in	in	in
4500	67	85	1.4	3.0	4.1	8.4	11.5	0.83	4.4	7.9	9.6
2400	537	74	1.6	3.7	4.7	8.9	12.5	1.3	4.7	11.0	13.7
3600	200	87	1.3	2.5	4.3	7.9	10.2	1.3	6.4	10.5	12.7
200	85	60	1.4	2.0	2.3	...	...	...	...	...	...
200	30	64	1.3	2.1	2.5	...	...	...	...	...	...
500	87	85	1.5	2.2	2.6	...	...	...	...	...	...
500	191	90	1.2	1.9	2.1	...	...	...	...	...	...
2000	89	15	1.7	3.2	4.0	9.8	14.9	...	...	...	...
900	325	70	1.1	2.7	3.1	5.3	...	...	...	...	...
3800	461	15	4.0	8.5	10.2	12.0	16.1	2.8	10.7	18.1	22.7
3500	9300	70	1.0	2.5	3.1	8.1	13.1	...	...	...	...
1600	2057	80	1.8	3.2	3.8	10.4	...	...	...	...	...
3400	1682	15	1.2	2.3	2.9	6.4	...	...	...	...	...
1400	2960	120	1.3	3.1	4.2	...	...	...	...	...	...
5000	4150	30	0.22	0.50	0.67	0.93	1.6	...	...	...	...
4500	4937	30	0.23	0.58	0.81	1.7	2.7	0.46	2.3	3.7	5.0
4100	668	20	2.5	5.7	7.1	10.8	14.8	3.1	9.0	16.7	23.8
2710	226	5	2.5	5.3	7.2	12.2	21.6	...	...	...	...
1740	940	90	1.1	2.7	3.7	6.4	11.5	...	...	...	...
4200	359	85	0.7	1.5	1.9	3.3	6.3	0.89	3.2	4.8	9.3
3200	124	10	1.6	3.1	3.7	5.6	9.9	...	...	...	...
4400	134	30	3.4	6.1	6.9	8.6	11.3	1.9	8.2	14.6	21.6
4300	188	70	2.1	4.6	5.6	8.2	12.0	...	...	...	...
4400	200	27	2.3	5.5	6.6	8.8	10.7	...	...	...	...
3000	68	42	3.5	8.3	10.2	14.8	20.4	...	...	...	...
3620	149	60	2.8	5.3	6.3	12.5	16.6	3.1	10.3	15.9	20.2
2400	147	90	1.9	3.9	4.8	7.6	12.6	...	...	...	...
5300	1983	37	0.96	2.4	3.1	5.2	10.2	...	...	...	...
5200	3611	45	1.9	4.8	6.3	11.3	18.0	2.6	9.3	16.6	23.2
5600	73	30	0.84	2.0	2.8	6.3	8.3	...	...	...	...
5800	746	95	0.6	1.6	2.1	2.9	5.8	...	...	...	...
4800	184	122	1.9	4.7	5.8	7.0	9.3	5.1	9.8	16.6	20.2
4000	145	10	4.0	8.6	10.1	14.9	17.8	...	...	...	...
5600	699	60	0.46	1.1	1.5	2.1	3.8	...	...	...	...
5600	795	60	0.49	1.3	1.8	4.3	6.6	...	...	...	...
5100	1351	75	2.0	4.1	5.3	7.7	9.3	2.4	9.3	16.5	21.3
4000	134	50	3.6	8.0	10.4	14.1	15.2	6.9	15.8	25.5	29.7
6800	40	135	3.7	7.2	8.6	8.8	11.1	...	...	...	...
4500	207	60	4.0	9.2	12.4[a]	16.5	17.7	6.5	15.8	22.7	28.0
4650	1201	50	3.4	8.9	10.7[a]	20.3	25.8	4.9	12.5	20.8	28.2
3650	36	75	4.1	7.8	10.0	16.0	18.7	...	...	...	...
6600	91	45	2.2	4.6	5.6	6.5	7.6	...	...	...	...
6000	214	60	3.6	8.8	10.4	14.5	17.7	...	...	...	...
5900	71	20	2.6	5.1	5.8	9.6	13.0	...	...	...	...
4400	9	135	5.8[a]	13.6[a]	16.2[a]	22.8[a]	26.9[a]	...	...	...	...
4700	12	10	4.9	11.5	14.5[a]	20.1	25.7	...	...	...	...
2500	84	80	2.9	4.9	5.6	14.1	17.9	...	...	...	...

(Continued)

Table 1--List of streams

No.	Stream	Index station	Year	Annual runoff
				in
96	Bear River	Near Wheatland	1906-. . .	22.6
97	North Fork American River	Near Colfax	1915-1941	34.2
98	North Fork American River	North Fork Dam	1942-. . .	35.4
99	North Fork American River	Rattlesnake Bridge	1930-. . .	32.9
100	American River	Fair Oaks	1905-. . .	27.4
101	Local American River	Fol.-Aub.-Cam.-Col.	1923-. . .	11.0
102	M. Fork American River	Near Auburn	1912-. . .	35.0
103	South Fork American River	Near Kyburz	1923-. . .	30.7
104	South Fork American River	Near Camino	1923-. . .	26.9
105	South Fork American River	Coloma	1930-1941	25.4
106	Silver Fork American River	Near Kyburz	1925-. . .	29.9
107	Alder Creek	Near Whitehall	1923-. . .	23.8
108	Plum Creek	Near Riverton	1923-1940	20.0
109	Silver Creek	Union Valley	1925-. . .	38.0
110	Silver Creek	Near Placerville	1922-. . .	35.5
111	South Fork Silver Creek	Near Ice House	1925-. . .	39.2
112	North Fork Cache Creek	Near Lower Lake	1930-. . .	13.4
113	Cache Creek	Capay	1906-. . .	8.4
114	Putah Creek	Guenoc	1904-1906, 1930-. . .	25.6
115	Putah Creek	Near Winters	1905-. . .	13.3
116	Conn Creek	Near St. Helena	1931-. . .	8.2
117	Eel River	Scotia	1911-. . .	27.6
118	Van Duzen River	Bridgeville	1912-1913, 1939-. . .	40.0
119	Salmon River	Somesbar	1912-1913, 1929-. . .	27.6
120	Trinity River	Lewiston	1912-. . .	28.8
121	Trinity River	Near Hoopa	1912-1918, 1932-. . .	31.2
122	Smith River	Near Crescent City	1931-. . .	66.2
123	Santa Ana River	Near Mentone	1896-. . .	6.7
124	San Gabriel River	Near Azusa	1894-. . .	10.9
125	Arroyo Seco	Near Pasadena	1910-. . .	9.1
126	Piru Creek	Near Piru	1911-1913, 1934-. . .	2.3
127	Sespe Creek	Near Fillmore	1912-1913, 1928-. . .	6.9
128	Ventura River	Near Ventura	1912-1913, 1929-. . .	5.6
129	Coyote Creek	Near Ventura	1927-1932, 1933-. . .	5.0
130	Santa Ysabel Creek	Near Mesa Grande	1912-1928, 1936-. . .	6.9
131	Cuyama River	Near Santa Maria	1929-. . .	0.5
132	Huasna River	Near Santa Maria	1929-. . .	3.1
133	Salinas River	Near Santa Margarita	1922, 1932-. . .	4.3
134	Salinas River	Near Spreckles	1900-1901, 1929-. . .	2.3
135	San Antonio River	Pleyto	1929-. . .	6.4
136	Arroyo Seco	Near Soledad	1901-. . .	10.3
137	Uvas Creek	Near Morgan Hill	1930-. . .	16.0
138	San Lorenzo River	Big Trees	1937-. . .	15.3
139	Los Gatos Creek	Los Gatos	1930-1943, 1943-1944	14.6
140	Owens River	Near Round Valley	1904-1923, 1928-1940	6.8
141	Local Truckee River	Tahoe to Iceland	1899-. . .	16.4
142	Silvies River	Near Burns, Oregon	1903-1906, 1909-. . .	2.1
143	Caliente River	Near Bena	1943-. . .	1.0

and basic data (Continued)

Mean elevation	Area stream basin	Orientation	Maximum recorded depth runoff								
			Duration in days								
			Winter rain					Summer snow-melt			
			1	3	5	20	40	5	30	60	120
ft	sq mi		in	in	in	in	in	in	in	in	in
2200	295	55	3.2	7.8	9.3	15.9	23.7	3.3	6.8	9.1	10.9
4500	308	65	3.1	7.4	9.2	11.9	16.4	4.9	13.7	21.9	29.2
4700	343	65	2.1	4.5	5.5	9.6	11.7	. . .	. . .	. . .	. . .
4700	999	65	1.8	4.0	5.0	8.7	11.7	2.9	10.8	18.4	23.2
4400	1921	75	2.1	5.4	7.5	13.3	20.1	3.1	11.8	19.2	29.6
1700	497	90	2.6	5.0	6.4	10.8	12.4	. . .	. . .	. . .	. . .
5000	619	70	2.9	6.8	8.5	11.4	16.6	5.4	17.5	26.7	32.5
7800	196	95	1.2	2.1	2.4	3.3	5.7	. . .	. . .	. . .	. . .
6150	497	90	1.8	3.3	4.2	7.3	8.8	3.0	13.9	20.7	28.7
5300	635	90	1.1	1.9	2.2	4.4	6.7	. . .	. . .	. . .	. . .
7300	108	120	1.3	2.5	3.0	4.4	4.8	. . .	. . .	. . .	. . .
5800	23	135	1.2	3.3	4.3	8.1	12.4	. . .	. . .	. . .	. . .
4700	7	135	2.2	5.0	6.2	9.3	13.3	. . .	. . .	. . .	. . .
6200	83	75	2.5	4.7	5.2	8.7	14.6	. . .	. . .	. . .	. . .
5500	176	80	2.0	3.7	4.1	7.7	14.6	4.0	17.4	28.9	37.3
6800	28	95	2.2	4.0	4.9	7.6	8.7	4.2	17.9	31.6	42.4
2500	214	45	2.2	5.0	5.9	7.5	13.6	. . .	. . .	. . .	. . .
1600	1041	60	0.8	1.7	2.3	4.4	. . .	. . .	. . .	. . .	. . .
1720	113	45	6.0	7.3	8.2	19.6	29.4	. . .	. . .	. . .	. . .
1200	614	45	3.3	6.9	7.5	12.3	20.0	. . .	. . .	. . .	. . .
950	52	20	2.4	4.6	5.6	10.1	12.7	. . .	. . .	. . .	. . .
2480	3070	90	3.3	7.0	9.4	15.0	24.2	. . .	. . .	. . .	. . .
3320	200	140	3.1	6.9	9.4	18.1	33.2	. . .	. . .	. . .	. . .
4200	737	80	1.6	3.5	4.5	7.9	9.8	. . .	. . .	. . .	. . .
4700	724	15	1.8	4.0	5.1	8.5	11.0	. . .	. . .	. . .	. . .
3600	2840	30	1.4	3.4	4.7	8.3	11.5	. . .	. . .	. . .	. . .
2400	613	70	3.8	9.7	12.6	26.5	43.0	. . .	. . .	. . .	. . .
7000	189	45	3.0	5.1	5.6	7.8	. . .	. . .	. . .	. . .	. . .
4250	211	60	3.8	9.3	11.1	15.4	22.6	. . .	. . .	. . .	. . .
3500	16	15	6.0	9.5	10.9	15.7	. . .	. . .	. . .	. . .	. . .
4600	432	30	1.1	2.0	2.4	3.4	. . .	. . .	. . .	. . .	. . .
4350	254	60	2.2	3.8	4.8	9.0	. . .	. . .	. . .	. . .	. . .
2100	187	10	3.6	5.5	6.4	11.2	. . .	. . .	. . .	. . .	. . .
1450	41	40	3.3	5.5	6.8	6.9	. . .	. . .	. . .	. . .	. . .
3100	53	90	7.1	11.1	11.9	22.4	26.8	. . .	. . .	. . .	. . .
5250	912	120	0.22	0.34	0.37	0.63	. . .	. . .	. . .	. . .	. . .
1190	119	0	1.4	1.9	2.2	3.4	5.7	. . .	. . .	. . .	. . .
1900	148	135	1.8	2.5	3.0	4.6	. . .	. . .	. . .	. . .	. . .
1760	4231	135	0.61	1.3	1.6	2.7	. . .	. . .	. . .	. . .	. . .
1490	282	45	1.2	2.5	3.3	5.8	. . .	. . .	. . .	. . .	. . .
2400	241	100	2.9	5.4	7.3	9.5	11.6	. . .	. . .	. . .	. . .
1100	30	0	4.9	8.4	8.8	16.8	. . .	. . .	. . .	. . .	. . .
1250	110	15	4.6	7.6	8.7	10.8	. . .	. . .	. . .	. . .	. . .
1800	40	180	3.9	6.9	8.2	11.1	. . .	. . .	. . .	. . .	. . .
7600	450	120	0.08	0.16	0.24	0.66	1.0	. . .	. . .	. . .	. . .
6800	406	90	1.2	2.6	3.4	5.1	6.0	. . .	. . .	. . .	. . .
5000	924	5	0.08	0.19	0.26	0.72	1.2	. . .	. . .	. . .	. . .
4100	368	95	0.25	0.50	0.70	1.5	1.8	. . .	. . .	. . .	. . .

(Continued)

Table 1--List of streams

No.	Stream	Index station	Year	Annual runoff
				in
144	Palm Canyon Creek	Near Palm Springs	1930-1940	1.1
145	Deep Creek	Near Hesperia	1930-. . .	7.1
146	Mojave River	Near Victorville	1931-. . .	2.6
147	Mojave River	Barstow	1931-. . .	0.5
148	West Fork Mojave River	Near Hesperia	1930-. . .	6.8

Two General types of floods occur in California: (1) Those due primarily to rain and (2) those due primarily to snow-melt in the high mountains. Flood runoff primarily due to rain usually occurs between November 15 and April 15 and for convenience is referred to as winter rain runoff. The hydrographs of winter rain runoff floods are characterized by relatively high peak flows and are of short duration. Flood runoff due primarily to snow-melt usually occurs between April 15 and July 15 and for convenience is referred to as summer snow-melt runoff. Summer snow-melt hydrographs are characterized by relatively low peak flows and are of long duration and large volume. Below an elevation of about 5000 ft, summer snow-melt runoff volume is usually not of significant importance; while at elevations in excess of about 7000 ft winter-rain runoff is usually not of significant importance. Both of these two types of runoff were studied; however, summer snow-melt runoff data were in general not compiled for those stream basins having maximum elevation less than 4000 ft or for basins where very little snowfall occurs. For each of the selected stream gaging stations the maximum volume of runoff that had been recorded during periods of high water was tabulated for the following durations of time: 1, 3, 5, 20, and 40 days for winter rain runoff; 5, 30, 60, and 120 days for summer snow-melt runoff. The maximum volume of runoff that had been recorded from drainage areas located between gaging stations located on the same stream was in some instances computed. In order to facilitate the comparison of runoff volumes from different stream basins, runoff data were converted to inches of depth on the drainage area above or between gaging stations. Table 1 lists the maximum recorded depths of runoff for each duration of time. The greatest one-day winter rain runoff, shown on Table 1, was recorded on Santa Ysabel Creek in the extreme southern part of California; whereas the greatest 40-day runoff was recorded on the Smith River in the extreme northern part of California. The greatest one-day depth of winter rain runoff that has been recorded in California varies from 0.1 to 7.0 inches, and the greatest 40-day depth varies from 1.1 to 43.0 inches, ratios of about 70 and 40, respectively, This is an extremely large variation, far too great to be merely a matter of chance. By plotting the recorded depth of runoff against various indices and topographic features, general trends were brought out and much was learned concerning the effect of location and topographic factors on runoff.

Extensive use was made in this study of the depth-duration method of plotting runoff data. These depth-duration curves provided a check on the continuity of the runoff data and show how flood runoff varies with the location and the elevation of watersheds. Depth-duration runoff curves for eight typical streams are shown on Figure 2. These curves show that the San Gabriel River in Southern California at a medium elevation, facing the ocean, has a much larger winter rain runoff for all durations than Palm Canyon Creek which is also at a medium elevation and is located only a short distance to the east but is situated on the lee side of a mountain range. The Smith River in northern California, a low elevation stream facing the ocean, has a much greater and longer duration of winter rain and summer snow-melt runoff than occurs on the San Gabriel River. Streams at high elevation, like Bear Creek and Owens River, have a much greater summer snow-melt runoff than a winter rain runoff; while the reverse is true for streams like the Calaveras River located at a low elevation. Streams at medium elevations, like the Tule and Yuba Rivers, experience considerable runoff from both winter rains and summer snow-melt.

The topographic factors or indices influencing flood producing runoff in California, which were brought out by the various plottings of this study are as follows: (1) As the latitude increases there appears to be a general increase in long duration depth of flood runoff and a general decrease in short duration depth of flood runoff. (2) The higher in elevation and closer a windward barrier mountain ridge is to a stream basin, the less the depth of runoff from that stream basin.

and basic data (Concluded)

Mean elevation	Area stream basin	Orientation	Maximum recorded depth runoff								
			Duration in days								
			Winter rain					Summer snow-melt			
			1	3	5	20	40	5	30	60	120
ft	sq mi	°	in	in	in	in	in	in	in	in	in
4000	94	60	0.48	0.88	0.94	1.5	1.8	...	...	...	...
5800	137	90	3.3	5.7	7.0	12.1	14.3	...	...	...	...
3600	530	120	1.1	2.0	2.5	4.5	5.3	...	...	...	...
3100	1293	120	0.26	0.36	0.44	0.80	0.92	...	...	...	...
4000	75	90	3.5	6.2	7.4	12.6	14.8	...	...	...	...

[a] Considered to be inaccurate.

(3) Large basins (having an area of more than 100 sq mi) located on the back or lee side of a mountain range experience considerably less depth of flood runoff than large stream basins located on the front or windward side of a range, but small stream basins located within five or ten mi of the mountain crest experience about the same depth of runoff on either side. (4) Winter rain runoff depths in general reach their greatest values on stream basins located at a mean elevation somewhere between 3000 and 4000 ft, while summer snow-melt runoff depths reach their greatest values somewhere between 7000 and 9000 ft. (5) Stream basins in which the principal stream or in which most of the tributary streams flow south or slightly west of south apparently experience a larger depth of flood runoff than those in which the streams flow in other directions, with the minimum being experienced on those basins in which the streams flow in a northerly direction. (6) Large stream basins experience less average depth of flood runoff than correspondingly located small ones. (7) The presence of large lakes and swamps in a stream basin tends to reduce the depth of flood runoff. (8) Great depth of soil and great density of vegetative cover on a stream basin tends to reduce the depth of flood runoff.

Some of these factors like front and lee side exposure, height and distance of barrier ridges, are extremely difficult to evaluate numerically. Furthermore, most of them appear to be interrelated. For instance, stream basins that are located in a region of large annual precipitation will ordinarily have deep soil and dense vegetative cover; while those in an arid location will tend to have little soil or little humus in the soil and little vegetative cover, so that a much greater rate of precipitation is required to produce a given depth of runoff from the first type of watershed than is required for the second type.

Study of the various plottings of depth of runoff data against various factors and indices led to the conclusion that some direct measure of general wetness of a watershed was needed. The use of basin mean annual runoff or of basin mean annual precipitation was considered for this purpose, and the former was selected for use due to the relative accuracy of its measurement at gaging stations and the ease with which the result obtained by averaging the available runoff records could be adjusted to make the result representative of a long time average. Basin mean annual precipitation is difficult to compute and relatively inaccurate over much of a mountainous area such as California. Annual runoff in general proved to be a fairly good index for flood runoff, as it is a measure to some extent of factors which are difficult to evaluate, such as latitude and the effect of barrier ridges. It cannot, however, be successfully used alone to determine flood runoff but must be supplemented by other factors or indices. The selection of additional factors or indices was dependent on the time and manpower available for making this study; how readily the factors or indices could be evaluated from maps or other data; and how successfully each factor or index correlated runoff data from widely divergent stream basins. The factors or indices that were finally selected were the annual runoff and the mean elevation, size, and orientation of the stream basin.

It was not found possible to develop a formula for depth of flood runoff; so instead a graphical correlation diagram for each period of duration was developed, using the technique explained in detail by SPREEN [1947]. The basic runoff data for winter rain runoff were plotted for each stream, using its annual runoff and the mean elevation, size, and orientation of the stream basin as parameters. The correlation diagram which was developed for one-day winter rain runoff appears on Figure 3. The basic runoff data for summer snow-melt runoff were plotted for each stream using its annual runoff, and the mean elevation, and size of the stream basin as parameters. The correlation diagram which was developed for five-day summer snow-melt runoff,

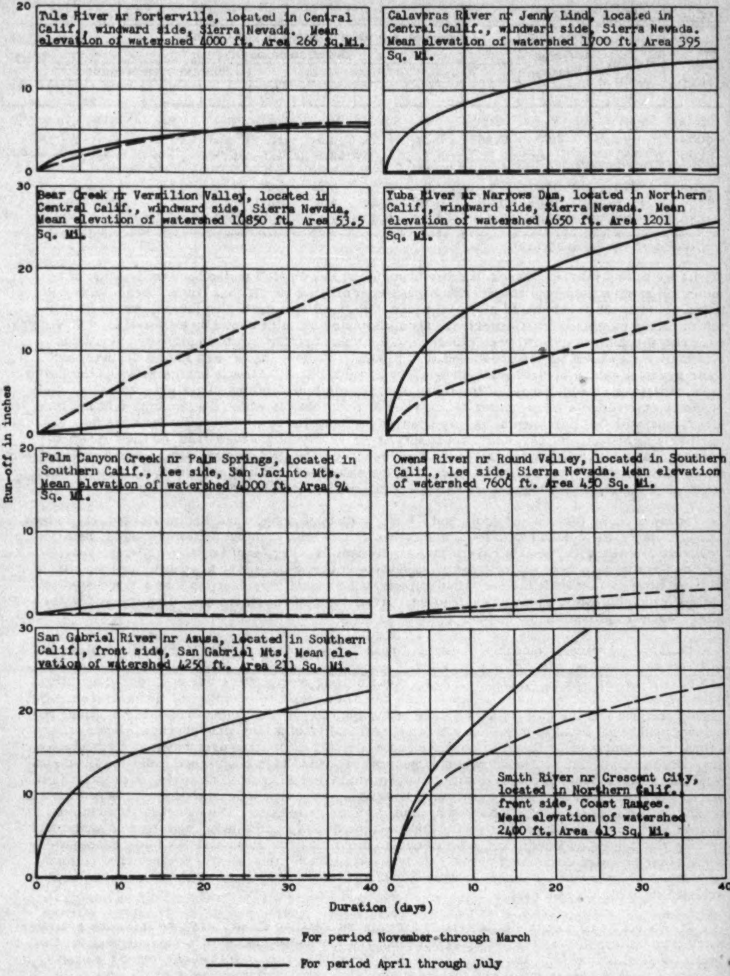

Fig. 2--Typical depth duration curves of maximum recorded runoff appears on Fig. 4. Even with the use of four parameters it was not found possible to develop a single graphical correlation diagram for winter rain runoff applicable to the entire State of California. For the same wetness, elevation, size, and orientation indices, streams in the Sacramento-San Joaquin Basin have considerably less depth of winter-rain runoff than have the streams located in the coastal ranges south of the Eel River and considerably more than the streams located in the coastal ranges north of the Eel River. It should be kept in mind that this statement is relative only, as low-volume runoff and high-volume runoff streams are found in all of these geographical areas; it is the relationship between runoff, and the parameters that follow the trends just mentioned. The graphical correlation diagrams for winter rain runoff of which one appears on Figure 3 and for summer snow-melt runoff of which one appears on Figure 4 are applicable to streams located in the Sacramento-San Joaquin Basin and to the streams lying somewhat beyond the east border of that basin but are not applicable to streams in the coastal ranges of California.

The depth of runoff from streams located in the Sacramento-San Joaquin Basin was determined by use of the graphical correlation diagrams and compared with the maximum recorded depth. For winter rain runoff, the maximum recorded depth from 16 streams or an average of about six for each period of duration studied (1, 3, 5, 20, and 40 days), is very nearly the same as the correlated value of runoff. These streams, where the correlated and recorded values of runoff are very nearly the same, form the control or establish the ceiling for each correlation diagram. The same situation holds true for summer snow-melt runoff where the recorded runoff from about 14 streams or an average of about six streams per diagram form the control or establish the ceiling. These controls are scattered throughout each correlation diagram and each determine the location of one particular section of a parameter. The basis for the establishment of intermediate values is one of logical symmetry. It is believed that the parameters of the natural factors affecting runoff must vary gradually and in a uniform manner. Many different patterns of possible parameter lines can be laid out, but so long as the principal of symmetry and regular curves is adhered to, it will be found that about the same answers will be given by any one of them.

To use these charts, proceed as follows: Determine the mean elevation of the stream basin in ft about sea level; determine its area in sq mi; determine the orientation by measuring the departure of the stream (viewed in an upstream direction) in degrees, either to east or west from the north; determine the average runoff from the runoff record. If no runoff record is available an approximate value of average annual runoff can be secured by determining the average annual precipitation over the stream basin by use of the general annual precipitation-annual runoff curve appearing on Figure 5. This was developed by plotting average annual runoff against average annual precipitation for streams in the Sacramento-San Joaquin Basin.

The various correlation diagrams are each entered first with the value of average annual runoff, and then with the other parameters of mean elevation, area and orientation (when applicable) in succession. The depth of runoff read from each of the correlation diagrams of a set are usually best plotted in the form of an envelope depth-duration curve similar to those appearing in Fig. 2. These envelope depth-duration curves are considered to establish the desired reference plane of flood runoff for the Sacramento-San Joaquin Basin.

Hydrographs of runoff equivalent in volume to the envelope depth-duration curve can be developed by various methods. The most reliable method is considered to consist of the augmentation of hydrographs which have been recorded on the stream in question. These hydrographs can be selected as the ones most likely to prove critical in regard to flood-control works. They are augmented sufficiently so that when plotted as depth-duration curves they become tangent to the envelope depth-duration curve (defined by the correlation diagrams) but do not rise above it at any point. When dealing with a stream basin for which hydrographs are not available, hydrographs produced by a stream basin having similar characteristics can be used. In this case it may be necessary to either augment or reduce hydrographs in order to obtain the desired tangential duration curve.

Two problems arise when dealing with streams of low-average annual runoff, becoming quite important for streams where it is less than two inches. The first problem is inability to read the correlation diagrams accurately due to all the parameters having a point in common at zero. This problem can be considerably reduced by replotting the diagrams to an expanded scale or on logrithmic paper. The second problem is the inability to determine a reliable figure for average annual runoff. Most such streams are intermittent, have sandy or gravelly stream beds in which sub-surface flow takes place past the gaging station. In some cases, for this type of stream it is best to compute the average annual precipitation on the stream basin in question and to use the value of average annual runoff given by the curve on Figure 5 rather than to use a value computed from the record at the gaging station.

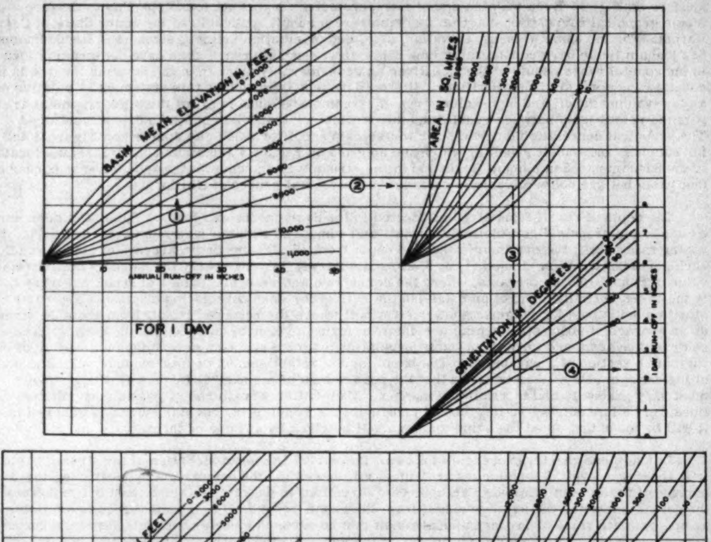

Fig. 3--Correlation curves for winter rain runoff, Sacramento-San Joaquin Basin (continued)

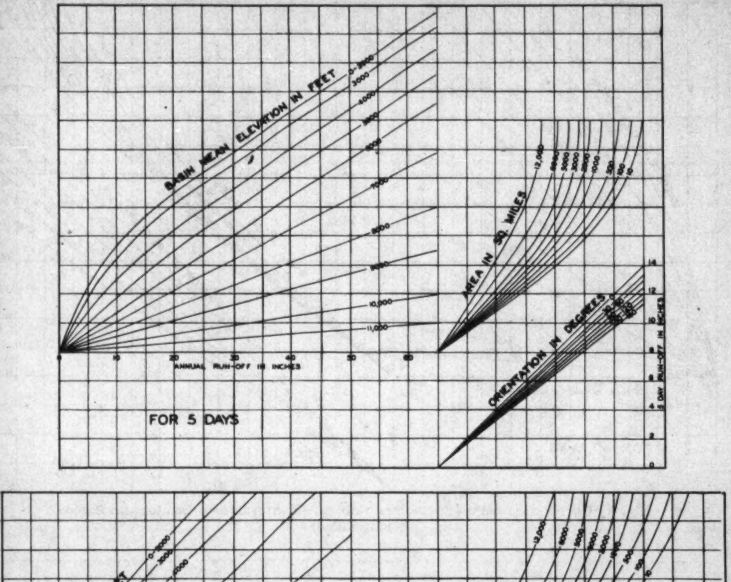

Fig. 3--Correlation curves for winter rain runoff, Sacramento-San Joaquin Basin (continued)

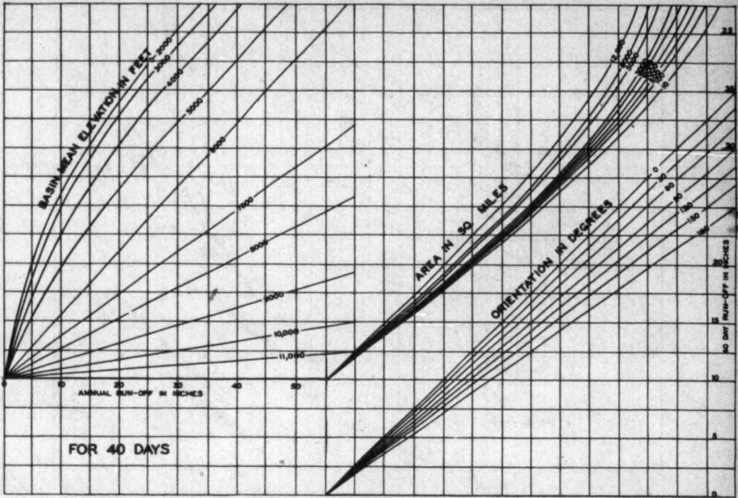

Fig. 3--Correlation curves for winter rain runoff, Sacramento-San Joaquin Basin (concluded)

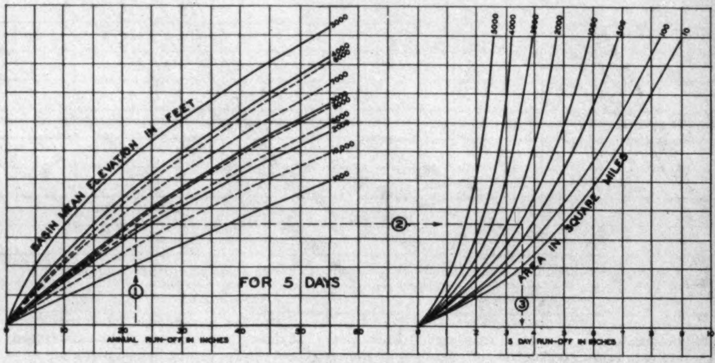

Fig. 4--Correlation curves for summer snow-melt runoff, Sacramento-San Joaquin Basin (continued)

A question which arose while making this study was the best method of dealing with the pre-record floods which occurred in 1862 in the Sacramento Basin and in 1867 in the San Joaquin Basin. On most of the major streams the stages reached are considerably in excess of any that have since occurred. It was decided to omit these floods from the basic data used in this study, as little data are available except high water marks, and estimates of the volume of flow vary widely.

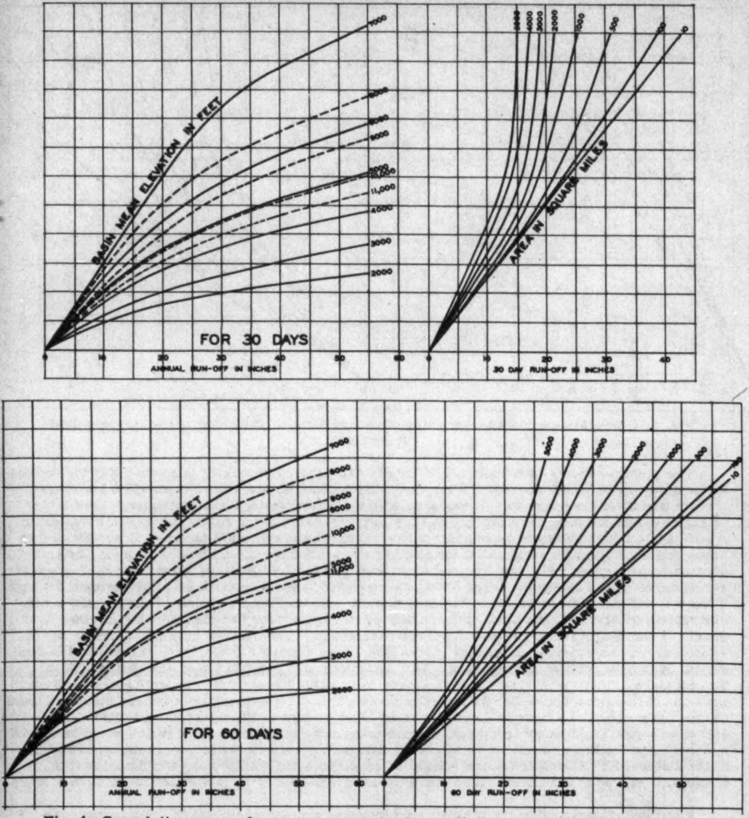

Fig. 4--Correlation curves for summer snow-melt runoff, Sacramento-San Joaquin Basin (continued)

The correlation diagrams which were developed are based on actually recorded runoff data from 148 stream-gaging stations for the period 1894 to date. If the ceiling for flood flows established by this data is not considered sufficiently high the entire series can be augmented to a higher level to include the floods of 1862 and 1867. This augmentation would probably be from ten to 25 per cent depending on what estimate of the volume of flow that occurred in these pre-record floods is accepted.

In conclusion some discussion is presented concerning; (1) the accuracy of runoff records and the present method of publishing revisions in water supply papers; (2) a frequency approach to the problem of establishing a reference plane for flood runoff; (3) the possibility of using other parameters or other methods of evaluating them; (4) why the use of correlation diagrams is considered superior to the method involving the tranposition or augmentation of storms.

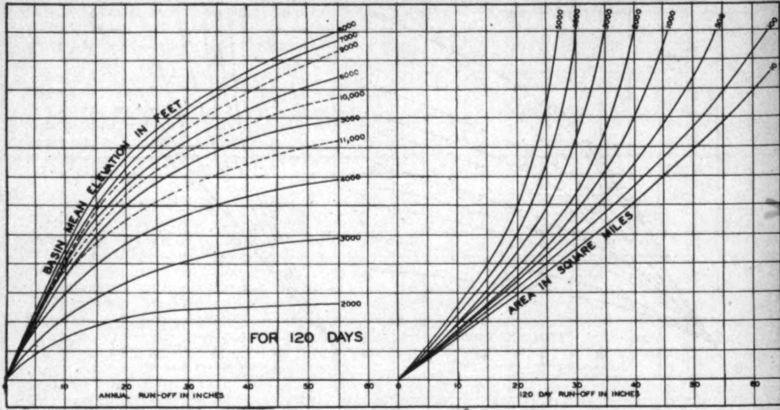

Fig. 4--Correlation curves for summer snow-melt runoff, Sacramento-San Joaquin Basin (concluded)

The greatest source of trouble and difficulty experienced in making this study was the question of the accuracy of runoff records. When the plotted points for the values of runoff from some stream basin were considerably at variance with the other points, a check was made on the type of gage used in obtaining the hydrograph stage, the extension of the rating curve which was used, runoff data from tributary or nearby streams, and precipitation-runoff factors. It was found that some published records, especially, for flood flows, needed revision, often, a very lengthy time-consuming procedure. For two long and important runoff records, it was found that the high-water rating curve in use during the large floods gave results in the neighborhood of 50 per cent too high. When a runoff record was questionable enough not to use as a control point, it often meant a considerable loss of time, as a week or more was often required for two men working together to develop a correlation diagram involving four parameters. The need for making extensive revisions and cross-references brought out that the present method in use by the United States Geological Survey in publishing revisions, notes, and comments in regard to runoff data, is inconvenient and makes it necessary for an engineer to do considerable time consuming research every time one of the older Water-Supply Papers is consulted. The Water-Supply Papers that were used in this study as well as those in constant use by other governmental agencies and private engineers, undoubtedly, in many instances, contain notes and corrections, all of which would be helpful to other users of these books. It is suggested that such private notes and corrections, in addition to the published revisions and notes, should be assembled and published by the United States Geological Survey in a form capable of being inserted in the Water-Supply Paper to which they apply.

A frequency approach to the problem of developing a reference plane of flood volume was attempted. In this approach, instead of using the maximum recorded depth of runoff at each station for plotting purposes, some selected frequency of occurrence was used; such as, once in 2, 10, 25, or 100 years. Frequency curves of the largest volume of runoff for durations of time of three and five days were prepared of winter rain runoff for some 60 streams. The method was eventually abandoned, however, as short length of runoff records eliminated the use of many streams; a very great deal of work was required to prepare the frequency curves; even for only the three and five-day periods; and a great personal equation was found to exist in the development of the upper end of the frequency curves.

It was recognized during the making of this study that other and perhaps better indices or ways of evaluating parameters might be possible. For instance, the use of average basin elevation as a parameter is rather a coarse index and that a system involving the percentage of areas in a given band or above and below a given elevation might prove to be better. Time and manpower limitations prevented investigating the possibility of this and other methods of evaluating the elevation

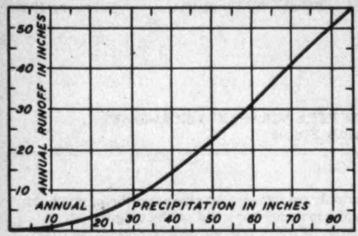

Fig. 5--Annual precipitation-runoff relationship for California

factor. Time and manpower limitations also prevented evaluating and investigating the possibility of using such factors as latitude, slope, and percentage of area in lakes and swamps as parameters in the correlation diagrams. The correlation diagrams for runoff which were developed in this study are imperfect and can, no doubt, be improved by the addition of more runoff data and by the addition of other parameters and by using other means of evaluating the parameters that were used.

Imperfect as the correlation diagrams for runoff may be, they are considered greatly superior in this region to the approach using transposition of storms and computation of flood hydrograph. The correlation diagram, by the very nature of its construction rests, as previously mentioned, on about 15 solid pillars of actually observed and runoff measured to the best ability of hydrographers. On the other hand, the precipitation approach rests on many separate assumptions. The first assumptions made in the precipitation approach involve the transposition of historical storms, a procedure where the assumptions are quite important in a mountainous area, like California, The next assumptions involve the initial condition of the stream basin, also very important for California. Early season precipitation over most of the State falls on a dry basin; in succeeding storms, it falls in part on a blanket of snow which varies in depth, density, and elevation. Assumptions involving infiltration rates are also extremely important; especially so, since the evaluation of infiltration rates is extremely unsatisfactory for large flood runoff. All the great floods of record in the Sacramento-San Joaquin Basin were preceded by one or more storms, and snow-melt and snowfall occurred at various times and at various elevations during the storm. Storm precipitation data for most of the mountain areas are extremely scanty, which, together with the complications involved by snowfall and snow-melt, make the evaluated infiltration rates extremely unsatisfactory. Furthermore, the soil cover of the large stream basins forms a mottled patchwork, varying widely in composition, depth, and degree of permeability. To sum up, it is necessary to make assumptions regarding the amount, rate, and distribution of precipitation, ground conditions, depth, density, and location of snowcover, rates of snow melt, and infiltration.

When the estimated limiting or optimum values of the factors concerned are asssumed to occur simultaneously, the resultant computed value of flood runoff is usually of astronomical magnitude. This is a very unsatisfactory situation, as at present there is no reliable method of establishing which, if any, of the factors are overestimated, or if the combination of events assumed is possible. The correlation approach, on the other hand, involves comparatively few and minor assumptions; and due to it resting on the pillars or control points previously mentioned, the results given by this method should never be extreme or absurd.

Acknowledgments--Many individuals took part in this study. The writer wishes to express his appreciation to Walter J. Parsons, Jr., Ralph R. Edwards, and Carl E. Schneider, who assisted in the technical aspects of the study, and Richard E. Bennion, Aubrey G. Carnefix, Bennett L. Johnson, Edwin C. Johnson, and Cleo C. Osborne, who assisted materially in the office engineering.

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Transactions, American Geophysical Union Volume 30, Number 1 February 1949

CLEAVAGE AND THE DISTORTION OF STRATIGRAPHIC THICKNESSES IN APPALACHIAN FOLDS

Jacob E. Gair

In a study undertaken by the writer in the central Appalachians, an attempt is being made to determine the effect which tectonic action--diastrophism--may have had on the original stratigraphic thicknesses of sedimentary rocks. This study, of which this account is merely an early progress report, has been initiated at the suggestion and under the most helpful guidance of Ernst Cloos.

The Paleozoic rocks with which the work is concerned are considered to be sedimentary in character, although they have been folded and fractured and rearranged to a greater or lesser degree. The major part of this problem deals with the cleavages which are developed in these folded Paleozoic rocks. By coming first to know, as nearly as possible, just what happened to the rock components to produce a given cleavage, inferences as to the effects on thicknesses of such changes as have produced the cleavage, should be more correctly drawn. The examination of the cleavage-thickness relationships in more or less completely exposed folds in the field is, perhaps, just as important as the reliance on such inferences. Deductions based on observations of small folds are assumed to hold for large folds which are never completely exposed.

In this report, brief mention is made of the methods by which this study is being furthered. During the 1947 field season a traverse was made across the central folded Appalachians. This traverse followed the valley of the Potomac River from Williamsport, Maryland, to Keyser, West Virginia (see Fig. 1). Excellent exposures were found in cuts of the western Maryland and the Baltimore and Ohio Railroads, and in a number of road cuts. Some of the observations thus far made are discussed. A microscopic examination of thin sections taken from the limbs and axial portions of folds is under way. Although a few tentative generalizations can now be made, the field work and microscopic examinations have not yet produced sufficient data for a general overall synthesis.

In respect to the relationship between cleavage and bedding, two general types of cleavage have been noted. The first of these types to be considered here is so-called fan cleavage. In folds in which this cleavage is developed (see Fig. 2), the cleavage is nominally parallel to the axial plane of the fold near that plane. However, in passing along the limbs of the fold, at a short distance from the fold axis, the cleavage is found to fan away from its position of parallelism with the axial plane. As the cleavage fans in this manner, it may intersect bedding at the same angle as in the axial portion of the fold, or it may make varying angles with bedding. Fan cleavage intersects the bedding at an angle of 90° close to the fold axis. Along the limbs this angle of intersection either will remain 90° or it will become less. As a general rule, the thickness of a given folded bed transected by fan cleavage is greatest where the angle between cleavage and bedding has its greatest value, and is least where the angle between cleavage and bedding has its least value. Although this relationship between the cleavage-bedding angle and the relative thickness of one part of a given bed as compared with another part of the same bed does obtain generally, nothing is implied as to a relationship between cleavage-bedding angles and absolute variations in thickness. In other words, in two similar folds the cleavage-bedding angle may vary at the same rate and by the same amount, but the changes in thickness in one fold are not proportional to the changes in thickness in the second fold (see Fig. 3). Where the cleavage-bedding angle remains constant through the fold, the thickness of bedding changes but little, if at all (see Fig. 4). Unless rock components such as ooids are found, components which are thought to record the amount of deformation rather accurately [CLOOS, 1947], the writer knows of no way to utilize the cleavage-bedding angle to determine the absolute amount of thickening or thinning in stratigraphic beds.

From an examination of thin sections taken from folds which have fan cleavage, it appears that there are two ways in which the cleavage has developed. Where rock components have been drawn or stretched out in the present cleavage plane, the whole rock seems to have flowed. Cleavage of this type appears to be predominant, at least as far west as the western edge of the Great Valley. In many cases a folded rock layer with fan cleavage will show no evident drawing

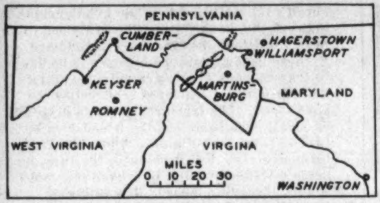
PENNSYLVANIA
CUMBER-LAND
HAGERSTOWN
WILLIAMSPORT
KEYSER
MARTINS-BURG
MARYLAND
ROMNEY
WEST VIRGINIA
VIRGINIA
MILES
0 10 20 30
WASHINGTON

Fig. 1--Map of area; the ridge to the west of Hagerstown, Maryland, marks the west border of the Great Valley

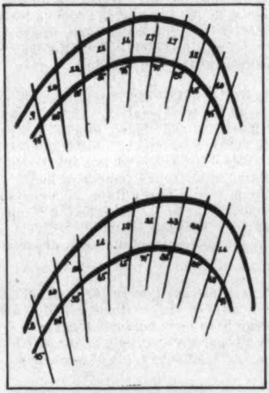

Fig. 3--Diagram illustrating the relationship between the cleavage-bedding angle and thickness variations in two similar anticlines

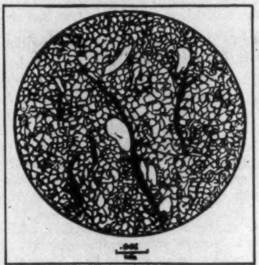

Fig. 5--Drawing illustrating the development of sub-parallel cleavage cracks in an impure limestone

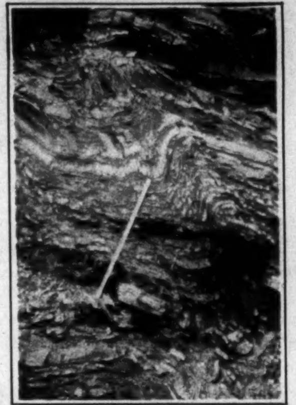

Fig. 2--Thin folded limestone bed with fan cleavage (above yardstick)

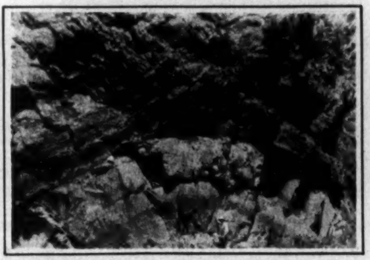

Fig. 4--Anticline in arenaceous shale in which fan cleavage remains practically at constant angle to bedding along the limbs of the fold (photo by E. Cloos)

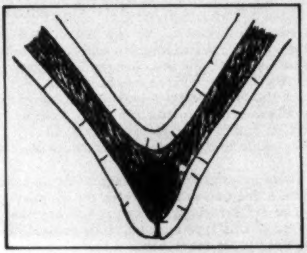

Fig. 6--Anticline showing development of cleavage in the less competent bed

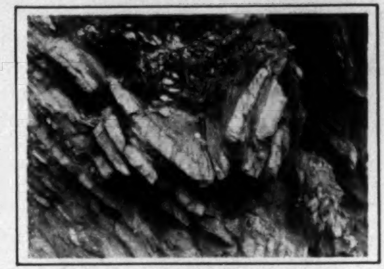

Fig. 7--Syncline showing the development of cleavage in less competent beds between more competent beds (photo by E. Cloos)

out of rock components. The relationships between the cleavage-bedding angle and thickness variations, however, are maintained. In these cases, cleavage appears to be due to the presence of many minute, irregular, but sub-parallel fractures transecting the rock layer. The fractures seem to originate as small openings along the boundaries between grains (see Fig. 5). When such fractures are very well developed, the rock, as seem microscopically, is broken into many small, irregular lenses. The following questions to which answers are not yet apparent now arise. Did intergranular flow so affect the rock that at some subsequent time fractures developed between grains, along surfaces which had carried the flowage movements, or did the folding produce fracturing directly? In this latter case, might post-fracturing movements along the fractures then have produced the observed variations in the thicknesses of the folded beds?

A second general type, other than fan cleavage, is typically developed in the Upper Silurian and the Upper Devonian rocks of the folded Appalachians west of the Great Valley. These rocks, which are often thinly interbedded sandstones and shales, or limestones and shales, display a cleavage which is developed in the less competent beds as they lie between un-cleaved more competent beds (see Fig. 6 and 7). It seems clear that the less competent beds served as a lubricating agent to facilitate the sliding movements attendant upon the folding of the more competent beds. As the more competent beds were folded, the configuration of the spaces between them, occupied by the incompetent beds, changed. At the same time that the shape of the areas between the competent beds changed, the incompetent material adjusted itself so as to continue to occupy entirely the spaces between the more rigid beds. Such adjustments of the incompetent material presumably account for the cleavage shown in Figure 6.

In concluding, emphasis again must be placed on the fact that any generalizations herein advanced are not as yet conclusive since they are based on scattered observations which to a certain extent have been fortuitous. In the past, studies of cleavage have been confined largely to metamorphic terranes. A continuing investigation of cleavage in non-metamorphic rocks should yield more and more information about the initial stages in the development of this phenomenon.

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(Manuscript received August 12, 1948; presented at the Twenty-Ninth Annual Meeting, Washington, D. C., April 22, 1948; open for formal discussion until July 1, 1949.)

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GEODETIC WORK ACCOMPLISHED IN MEXICO FROM APRIL 1947 TO MARCH 1948

Manuel Medina

(Translated by F. W. Darling)

In view of the development of the geodetic triangulation of Mexico, in which it has not always been possible to follow along parallels and meridians, due principally to the irregularity of the State boundaries in the Republic and to the rugged character of its terrain, we are working actively to finish a project of first order which comprises the arcs represented in Figure 1, in which the parts finished up to the end of 1947 are marked in solid black, and the part which is planned and in progress at the present time is marked with hachures.

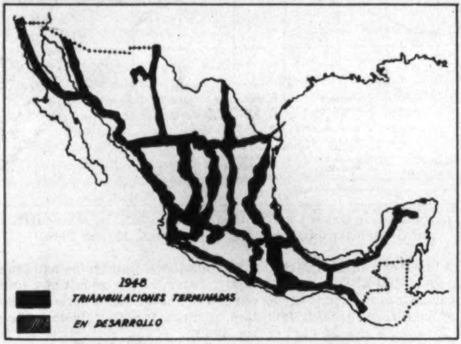


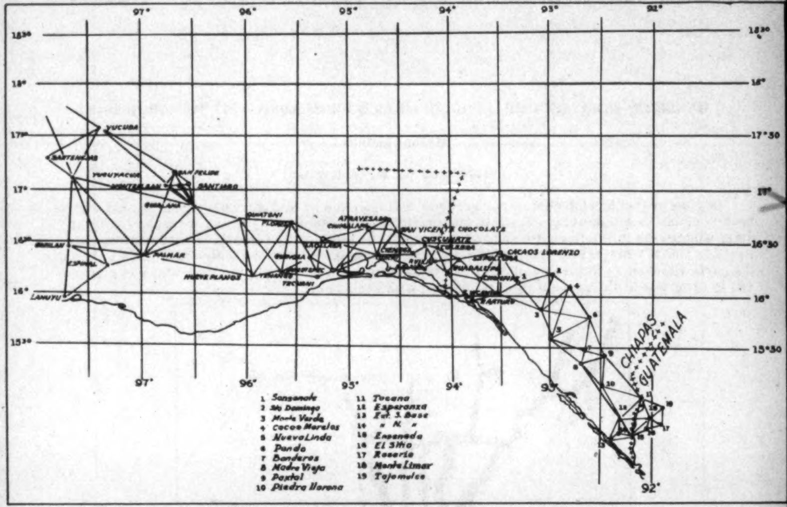
Fig. 1--Sketch of the triangulation in Mexico

In this general plan, the operations accomplished from April 1947 to March 1948 concerning triangulation, were the following:

Geodetic reconnaissance--In the State of Sonora, six figures (four quadrilaterals and two pentagons) are planned as a continuation of the triangulation of Sinaloa. The average length of the sides is about 60 km and all the vertices are situated on prominent points of the Sierra Madre Occidental. It is planned to extend this reconnaissance northwestward, parallel to the coast and dividing it into two branches at the latitude of Tiburon Island; one of these will go through the State of Sonora to the International Boundary with the United States, and the other will span the Gulf of California by way of the Tiburon and Angel de la Guarda Islands in order to prolong the reconnaissance through Baja California (Lower California) to its junction with the triangulation already existing in the northern part of the Territory.

In the States of Oaxaca and Chiapas, starting from the side, Palmar-Guialana, of the triangulation of the 98° meridian, a chain of geodetic figures was planned parallel to the coast as far as the boundary with the Republic of Guatemala. This interesting operation was in accordance with an agreement made at the Third Meeting of the Pan-American Conference held in Caracas, Venezuela, in 1946, which recommended the connection of the Mexican and Guatemalan triangulation.

The most rugged part, that is, the geodetic reconnaissances across a craggy sierra, has been finished and is shown in Figure 2.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SAN FELIPE
PALMAR
ESPINAL
LANUYU
NUEVE PLANOS
QUIATONI
TECUANI
ATRAVESADA
SAN VICENTE CHOCOLATE
CACAOS LORENZO
CHIAPAS
GUATEMALA
1 Sansanate
2 Sto Domingo
3 Monte Verde
4 Cacao Morelos
5 Nuevo Linda
6 Panda
7 Banderas
8 Madre Vieja
9 Paxtal
10 Piedra llorona
11 Tucana
12 Esperanza
13 Ext. S. Base
14 " N. "
15 Ensenada
16 El Sitio
17 Rosario
18 Monte Limar
19 Tajomulco

Fig. 2--Sketch of triangulation in Oaxaca and Chiapas which links the triangulation nets of Mexico and Guatemala (observations in progress, March 1948)

In the vicinity of the Mexican Boundary, the Guatemalan Commission had planned a geodetic base between the points called El Sitio and El Pajal. Later, as the result of a joint study by the Mexican and Guatemalan Commissions, it was agreed to change the location of the above base to Mexican territory, which offered greater facilities, locating it definitely upon the road that exists between the town of Tapachula and the port of San Benito.

In the State of Coahuila, along with the measurement of the angles, the reconnaissance of a triangulation scheme between the 101st and 102nd meridians was continued. At the present time, the arc has been completed relatively close to the Rio Bravo del Norte (Rio Grande), as shown in Figure 3.

Measurement of angles--Geodetic stations were established in the State of Sinaloa at the following vertices: La Vieja, San Miguel, El Carrizal, Huaco, Algodones, S. Antonio, and Cupido.

These observations were made with the Wild T-3 theodolite, 32 sights at each vertex (weight 16), and getting an average mean probable error of ±0.26 sec.

In the State of Coahuila the following stations were occupied: Mesa de Cartujanos, Buenavista, Salsipuedes, La Silla, Guangoche, Candela, Hermanas, Picacho de Luis, La Popa, and Aguadulce. These observations were also made with the theodolite, Wild T-3, weight of the observations, 16; and with an average mean probable error of ±0.28 sec.

In the State of Chiapas the following geodetic stations were established on the triangulation connecting that of Guatemala: Extremo N. de la Base, Esperanza, Extremo S. de la Base, Paxtal, Ensenada, and Piedra Llorona. These observations were also made with the Wild T-3 theodolite, wiehgt of the observations, 16; and with an average mean probable error,of ±0.26 sec.

Geodetic bases--The geodetic base of Tapachula was measured between the vertices Extremo N and Extremo S. Geodetic towers 33 m in height were installed for the angle measurements. The

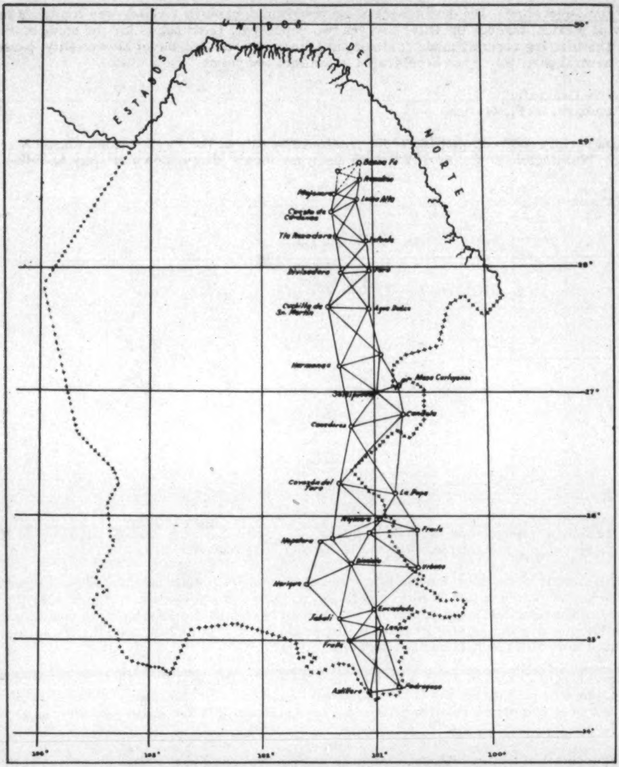
ESTADOS UNIDOS DEL NORTE
30°
29°
28°
27°
26°
25°
24°
104°
103°
102°
101°
100°
Loma Alta
Cuchilla de Sn. Martin
Agua Dulce
Hermanas
Mesa Cartujanos
La Popa
Fraile
Sabali
Escondido
Pedregoso

Fig. 3--Triangulation in the State of Coahuila (in progress)

base had a length of 13,549.7919 m and was measured with a relative error of 1:3,500,000.

Fifty-meter, invar-steel tapes of the United States Coast and Geodetic Survey were used. The measurement of this base was made with personnel of the Inter-American Geodetic Survey and of the Mexican and Guatemalan Commissions. The result of this measurement should be considered as provisional, while in the meantime a new standardization of the tapes used is being made.

Exploratory astronomy--For cartographic purposes and the demarcation of private concessions for the development of the national lands, the following astronomical stations were established: Central Aguilar, Q. Roo; Kilómetro 50, Q. Roo; Chen Cobre, Q. Roo; Puerto Vallarta, Jal.; Polyuc, Q. Roo; Jiménez, Coah.; El Moral, Coah.; Villa Acuna, Coah.; and Zaragoza, Coah.

The methods and instruments used for these preliminary positions were: Determination of the time by sextant observations of equal altitudes of the Sun, and altitudes of the polar star determined with a Wild theodolite of one-second approximation. The probable errors obtained in longitude as well as in latitude were about ±2 seconds on the average.

Precise leveling--The devlopment of the program of precise leveling was continued in the Valley of Mexico, through the City, between two supposedly fixed points for the study of the subsoil. The leveling recently made continues to show a gradual sinking of Mexico City, particularly in the central part, which has accelerated in the last few years.

Oficina de Geografia,
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THE LOOP CLOSURE OF THE GULF OF ST. LAWRENCE TRIANGULATION NET

C. H. Ney

One of the first operations of the Geodetic Survey of Canada after its inception in 1905 was the establishment, on a local datum, of the Dusable-Haldimand net extending from east of Montreal to slightly west of Kingston. In 1913, this net was connected in the Montreal area to the stations, Royal and Bellevue, comprised in the United States Coast and Geodetic Survey network. This connection was of great importance, as it made possible the establishment of the Canadian triangulation on the North American datum, which had been adopted that same year by Canada, the United States, and Mexico.

From this beginning, a primary net was extended northeasterly along the St. Lawrence River (see Fig. 1), till in 1923 the triangulation was terminated in the neighbourhood of Anticosti Island in the Gulf of St. Lawrence. Three of the stations comprised in this net, located near the eastern tip of Gaspé County, Quebec, were then used as a basis for the extension of a net towards the south. This net was projected through eastern New Brunswick to terminate in 1926 at the stations Shepody and Salem, which had already been comprised in the net of Bay of Fundy. The junction of the two primary nets at Shepody-Salem marked one of the first loop closures of Canadian geodetic triangulation.

The primary net of the Bay of Fundy had been started in 1909 at the United States Coast and Geodetic Survey stations Chamcook and Trescott Rock, situated near the New Brunswick-Maine border. By 1919, this net was projected as far as the eastern end of Minas Basin, where it terminated on the line Londonderry-Barr, not far from the stations Shepody and Salem.

From the adjusted line, Londonderry-Barr, primary triangulation was continued easterly and northeasterly, from 1920 to 1923, to the northeast tip of Cape Breton Island. In 1923 and 1924, a connection was made across Cabot Strait to Newfoundland, where two primary stations, Cape Ray and Cape Anguille, were established as a basis for geodetic work in that country. The longest line involved in the geometrical figure spanning Cabot Strait was 91.6 mi. In spite of the length of line, the observers had no difficulty in making their directional measurements in clear weather. The lights from the signal lamps marking the opposite ends of the line were easily visible to the naked eye.

In 1935, in conformity with the terms of an agreement with Newfoundland, officers of the Geodetic Survey of Canada, in collaboration with the Newfoundland Geodetic Survey, commenced the extension of an arc of primary triangulation up the west coast of Newfoundland, based on the line Cape Ray-Cape Anguille. The projection of this arc was discontinued in 1941 and 1942, due to the War, but was finally completed in 1944 on the line Parent-Forteau, near the north shore of the Strait of Belle Isle.

In 1941, commencing from the line Birch-Martin, at the Anticosti Island end of the Lower St. Lawrence net, an arc of primary triangulation was projected easterly for 300 mi to make a junction at the Strait of Belle Isle, on the line Parent-Forteau, with the Newfoundland west coast net.

The triangulation, extending from Anticosti Island along the north shore of the Gulf of St. Lawrence to the Strait of Belle Isle, was divided into three sections, each of which was subjected to a preliminary adjustment including angle, side, length, and Laplace condition equations. Similarly, the Newfoundland west-coast triangulation was divided into three sections, each with condition equations of a similar type.

The closure in position at the Strait of Belle Isle--Table 1 shows the latitude and longitude of the station Parent after the completion of the preliminary adjustments.

The closures of 0.″059 in latitude and 0.″536 in longitude represent six and 34 ft, respectively, in the meridian and prime vertical planes, or a hypotenuse distance of 34.5 ft.

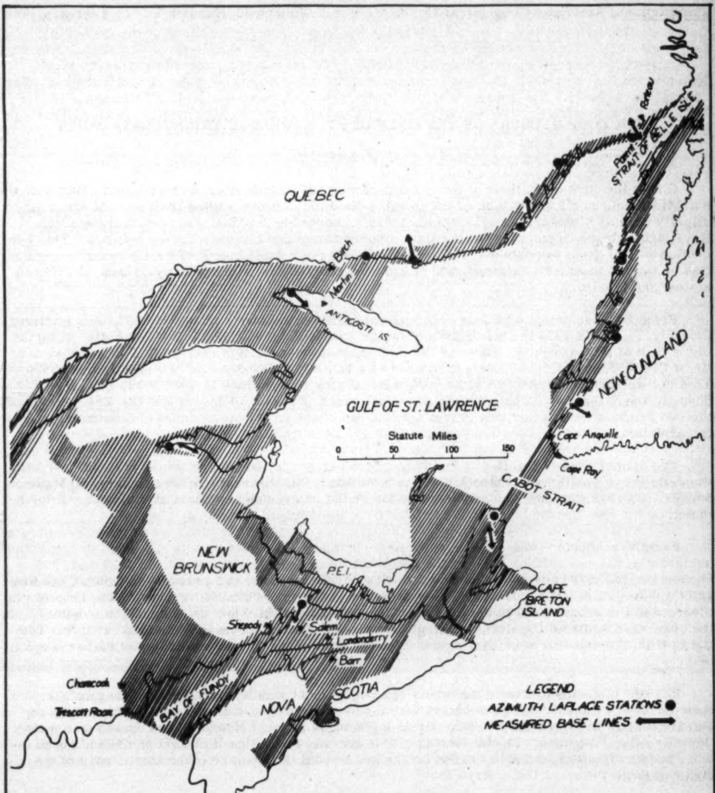
QUEBEC
Birch
Martin
ANTICOSTI IS.
Pointe
Forteau
STRAIT OF BELLE ISLE
NEWFOUNDLAND
GULF OF ST. LAWRENCE
Statute Miles
0
50
100
150
Cape Anguille
Cape Ray
CABOT STRAIT
NEW BRUNSWICK
P.E.I.
CAPE BRETON ISLAND
Shepody
Salem
Londonderry
Barr
Chamcook
Trescott Road
BAY OF FUNDY
NOVA SCOTIA
LEGEND
AZIMUTH LAPLACE STATIONS ●
MEASURED BASE LINES ⟷

Fig. 1--Map showing general scheme of triangulation in the area of the Gulf of St. Lawrence

Table 1--Latitude and longitude of the station Parent by two routes

Station	Route	Latitude	Longitude
		° ′ ″	° ′ ″
Parent	North Shore	51 25 16.574	57 09 43.263
Parent	Newfoundland	51 25 16.516	57 09 42.727
	Closure	- 0.058	- 0.536

As the total axial length of the series of nets, encircling the Gulf of St. Lawrence and meeting at the common line Parent-Forteau, is about 1300 mi, the ratio of the discrepancy in closure to the axial length is 1/198,000. As the section of the loop extending southerly from Anticosti Island through New Brunswick and Nova Scotia to the southern tip of Newfoundland had already been

subjected to a loop closure adjustment involving some of the eastern nets of the United States Coast and Geodetic Survey, it was held fixed in the loop-closure adjustment of the Gulf of St. Lawrence nets. The discrepancy in closure, as indicated by the values shown for station Parent, was distributed through the six component sections 603 mi in length, extending from Anticosti Island to the Strait of Belle Isle and thence southerly to the southwest point of Newfoundland. The absorption of the 34.5 ft closure, over a distance of 603 mi, corresponds to a ratio error of 1/92,000. Each section of the loop from Anticosti Island to the southwest tip of Newfoundland was made to absorb a proportional share of the closure depending upon its axial length.

The co-ordinates of Parent resulting from the loop-closure adjustment are: Latitude, 51°25′16.″555; longitude, 57°09′42.″998.

Closure in azimuth--From the preliminary adjustments of the portions of the loop west and south of the Strait of Belle Isle, the calculated azimuths of the common line, Parent-Forteau, were as shown in Table 2.

Table 2--Azimuth of Parent-Forteau line by two routes

Line	Route	Azimuth
		° ′ ″
Parent-Forteau	North Shore	45 54 37.421
Parent-Forteau	Newfoundland	45 54 36.114
	Difference	+ 1.307

Table 3--Length of Parent-Forteau by two routes

Line	Route	Log length
		•
Parent-Forteau	North Shore	4.0690558
Parent-Forteau	Newfoundland	4.0690382
	Difference = d log s = +	0.0000176

The insignificance of the closure in azimuth is undoubtedly due, to a large extent, to the corrective effect of Laplace stations introduced at intervals of about 90 mi along the axes of the nets.

Closure in length--From the preliminary adjustments, the length of the line, Parent-Forteau, was deduced independently from computation over the two routes as shown in Table 3.

As $d \log s = M \cdot ds/s$, where M is the modulus of common logarithms, we have $ds/s = d \log s/M = 0.0000176/0.4343 = 1/25{,}000$.

As the easterly end of the North Shore chain of triangulation had a measured base at Bradore, close to the line, Parent-Forteau, the log length of this line, 4.0690558, derived through the North Shore route, was held fixed in the final loop closure adjustment. The value 4.0690382, derived from the preliminary adjustment of the most northerly section of the Newfoundland arc, was without benefit of measured base-line control near the north end. For this reason, the rather large closure in length of 1/25,000 should be interpreted as an indication only of the approximate closure.

The best indication of the accuracy of the loop of triangulation as a whole is the small discrepancy in position of Parent as derived from computation over the two routes. The indicated closure of 1/198,000 is highly satisfactory. It shows that a high standard of accuracy was maintained in observing the horizontal directions. It also shows that the inclusion of adequate base line and Laplace azimuth checks in the component nets of the loop are invaluable in maintaining the general precision at the desired level.

As each component net of the loop was made to absorb its proportional share of the loop closure discrepancy, latitude and longitude equations were added to the preliminary adjustment by a differential method of solution. An azimuth and a terminal length equation were also included in the differential adjustment of each component net to ensure that the azimuth and length of each terminal line would be held fixed at the values derived from the preliminary adjustments.

Distribution of length and Laplace controls in loop--In the section of the triangulation extending southward from Anticosti Island through Quebec, New Brunswick, and Nova Scotia, the geometrical figures were relatively large with triangle sides averaging 23 mi in length. On this section, the Laplace azimuth stations and the measured base lines are spaced about 214 mi apart.

On the west coast of Newfoundland, the triangle sides average about 20 mi in length and the Laplace stations are at intervals of 85 mi and base lines at intervals of 125 mi.

On the section extending along the north shore of the Gulf of St. Lawrence from Anticosti Island to the Strait of Belle Isle, the average triangle side is about 12 mi in length. To compensate for the short lines, Laplace controls have been established at intervals of about 57 mi and measured base controls at intervals of about 93 mi.

The inclusion of numerous small triangles in the section of triangulation extending from Anticosti Island to the Strait of Belle Isle was not conducive to the easy maintenance of the required standard of accuracy. About 10 mi inland in most places, a range of low hills paralleled the coast line, so that geometrical figures involving sides of 25 or 30 mi could not be used. Instead, many of the triangle sides were necessarily short, sometimes only six or eight mi. To prevent errors in the measurement of the horizontal directions resulting from the use of signal lamps, suitable only for long lines, a special type of "flash-light" signal lamp was designed. This lamp consisted of an ordinary, pre-focused, two-cell electric torch mounted on a suitable frame and wired electrically so that it could be connected to an exterior source of battery power and an automatic time switch. This type of lamp proved very satisfactory and provided sufficient light, if properly lined up, for lines up to 20 mi in length.

By decreasing the average intervals between Laplace azimuth stations and measured baseline controls to 57 and 93 mi, respectively, the accuracy of the North Shore section of the Gulf loop has been maintained at the desired level.

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PROGRESS REPORT OF THE JESUIT SEISMOLOGICAL ASSOCIATION FOR THE YEAR 1947

J. B. Macelwane and Ross R. Heinrich

The year 1947 marked a gradual return to normal conditions throughout the scientific world; particularly in the United States was this noticeable.

The member stations of the Jesuit Seismological Association whose activities had been largely disrupted by the War not only resumed their normal operations but were taking steps to improve.

New equipment was installed at Fordham University (New York); at Canisius College (Buffalo); at John Carroll University (Cleveland); and at Saint Louis University (St. Louis). The two Macelwane-Sprengnether horizontal components loaned to Regis College, Denver, by Saint Louis University are functioning satisfactorily. Excellent records are being secured at Mount Saint Michael's (Spokane) with the long-period Wood-Anderson seismographs loaned to the Jesuit Seismological Association by the University of Wisconsin. At Loyola University of the South (New Orleans) the two long-period horizontal component Sprengnether seismographs are functioning well but the short-period vertical is so greatly disturbed that it has not been operated. The stations at Boston College (Weston, Massachusetts), at the University of Santa Clara (California), at Spring Hill College (near Mobile, Alabama), at Georgetown University (Washington), Xavier University (Cincinnati), and at Loyola University (Chicago) have been operated as usual.

The Central Station at St. Louis has maintained the three-cornered arrangement with Science Service and the United States Coast and Geodetic Survey for the immediate location of epicenters and has finally caught up with the back log of Preliminary Bulletins. During the year 1947 a total of 128 epicenters were determined and 105 Preliminary Bulletins were published.

The two deepest earthquakes of the year were in South America, the one on January 29 in northern Argentina, the other on August 6 in western Brazil, both having a focal depth of 600 km. Another earthquake of 400 km depth occurred on July 25 in northern Argentina; and another of 450 km depth occurred on February 18 in the Pacific Ocean south of the main island of Japan.

Figure 1 shows the geographic distribution of epicenters located during the year. The epicenters listed in the Bulletins of the Jesuit Seismological Society for 1947 are given in Table 1.

Table 1--Jesuit Seismological Association epicenters for 1947, preliminary

Bull. No.	Date	Epicenter		Time (U.T.)	Depth	Remarks
		Lat.	Long.			
	1947	°	°	h m s	km	
1	January 3	44.5 N	149.1 E	02 17 11		Deep?
2	January 15	27.5 N	111.6 W	18 28 07		
3	January 21	22.8 S	69.2 W	20 07 01	100	
4	January 23	52.0 N	163.3 W	16 57 40		
5	January 25	13.4 N	87.5 W	03 52 39		
6	January 26	13.5 N	86.7 W	10 06 46	75 ±	
7	January 29	27.0 S	62.8 W	08 17 50	600 ±	Northern Argentina
8	Supplement for January contains:					
	January 16	6.9 N	82.1 W	15 22 23		
	January 20	28 N	116 W	10 41 42		
9	February 16	16.8 N	97.1 W	02 15 48	80 ±	
10	February 24	15.0 S	68.2 W	17 31 36	50 ±	
11	Supplement for February contains:					
	February 3	9.9 S	76.0 W	16 42 36	200 ±	Peru
	February 7	10.1 S	161.9 E	08 40 40	50 ±	
	February 18	33.2 N	138.2 E	13 30 29	450 ±	South of the main island of Japan
	February 26	11 N	88.5 W	01 50.6		
12	March 2	5.5 S	144.5 E	19 09 27		
13	March 17	33.0 N	99.5 E	08 19 38		

(Continued)

Table 1--Jesuit Seismological Association epicenters for 1947, preliminary (Continued)

Bull. No.	Date	Epicenter		Time (U. T.)	Depth	Remarks
		Lat.	Long.			
	1947	°	°	h m s	km	
14	March 25	38.6 S	178.2 E	08 32 15		
15	Supplement for March contains:					
	March 22	20.5 S	73 W	09 41 57		Deep?
	March 23	11 N	90 W	01 17 35	100 ±	Guatemala Deep
16	April 2	1.8 S	138.3 E	05 39 16		
17	April 10	34 57′N	116 37′W	15 58 05		Pasadena
18	April 14	44.0 N	149.7 E	07 15 46	50 ±	
19	April 24	7.6 N	39.0 W	19 35 14		Deep?
20	Supplement for April contains:					
	April 26	15 N	102 W	13 19 18		
21	May 2	53.8 N	164.3 W	02 19 06	50 ±	
22	May 6	7 S	149 E	20 30 39		
23	May 8	3.0 N	95.1 W	23 52 58		Deep?
24	May 17	40.0 S	177.9 E	07 06 53		
25	May 27	2.4 S	141 E	05 59 14		
26	Supplement for May contains:					
	May 2	14.8 N	94.9 W	01 30 50		
	May 3	31.3 N	140.8 E	09 35 17		
	May 27	40.2 N	123.8 W	20 58 44		
27	June 5	13.8 N	89.9 W	22 58 18	100 ±	West of El Salvador
28	June 7	11.9 N	124.1 E	18 47 58		
29	June 12	1.0 N	126.5 E	09 02 34	100 ±	Moluccas
30	June 13	21.7 N	145.0 E	20 24 51		
	Aftershock			23 50 25		
31	June 19	21.7 N	145.0 E	07 34 39		
32	June 19	3.5 N	101.7 W	22 47 44	300 ±	Eastern Pacific Ocean west of Colombia
33	Supplement for June contains:					
	June 10	40.7 N	28.9 W	19 40 39		
	June 20	31.2 N	43.1 W	13 34 32		
34	July 10	73 N	67 W	10 48 43		
35	July 10	13.9 N	92.9 W	16 05 10	100 ±	Guatemala Deep
36	July 24	54.8 S	28.9 W	08 39 58		
37	July 12	45.0 N	150.3 E	01 59 02	50	
38	July 12	20.0 S	176.3 W	12 29 36		
39	July 13	19.7 S	178.8 W	12 57 30	150 ±	Tonga-Fiji
40	July 23	18.7 N	68.1 W	05 13 34		
41	July 23	55.3 S	28.5 W	17 13 22		
42	July 24	19.1 S	170.2 E	12 16 57		
43	July 25	23.5 S	65.4 W	19 08 47	400 ±	Northern Argentina
44	July 28	62.9 N	145.9 W	03 49 02		
45	July 29	28.2 N	93.2 E	13 43 24		
46	July 31	2 N	84 W	14 13 11		
47	Supplement for July contains					
	July 13	15.4 N	92.6 W	06 20 04		
	July 16	32.6 N	135.0 E	19 20 41		
	July 24	19.1 S	169.4 E	10 40 00		
	July 24	34.0 N	116.5 W	22 10 46		
	July 31	39.1 N	15.4 E	07 54 51	300 ±	In Mediterranean Sea, North of Sicily
48	August 5	24.2 N	61.2 E	14 24 14		
49	August 6	8.6 S	70.3 W	05 47 03	600 ±	Western Brazil
50	August 7	19.8 N	75.7 W	00 40 22		
51	August 9	1.5 N	29.7 W	02 48 28		
52	August 10	42.0 N	84.7 W	02 46 40		
53	August 27	37.8 S	179.1 E	13 37 48		
54	August 28	51.3 N	156.6 E	06 50 36	60 ±	
55	August 28	54.0 N	160.1 E	14 29 43	50 ±	
56	August 28	29.9 S	70.8 W	19 48 13	100 ±	Chile
57	Supplement for August contains:					
	August 1	27 N	112 W	14 25 15		
	August 16	15.4 N	96.1 W	18 45 28		
	August 18	4.0 S	106.7 W	06 08 53		
	August 22	9.7 S	165.6 E	02 31 36	100 ±	
	August 30	36.0 N	23.6 E	22 21 43	50 ±	

(Continued)

Table 1--Jesuit Seismological Association epicenters for 1947, preliminary (Concluded)

Bull. No.	Date	Epicenter		Time U. T.			Depth	Remarks
		Lat.	Long.					
	1947	°	°	h	m	s	km	
58	September 2	20.3 S	175.4 W	14	32	40	250 ±	Tonga
59	September 3	11.7 S	164.0 E	18	56	30		
60	September 4	15.7 S	173.4 W	00	30	14		
61	September 22	43.1 N	126.5 W	02	16	19		
62	September 23	53 N	162.7 W	07	41	47		
63	September 23	34.1 N	57.6 E	12	28	22		
64	September 23	40.2 N	125.8 W	13	52	58		
65	September 26	21.7 N	122.4 E	16	01	52	150 ±	East Formosa
66	Supplement for September contains:							
	September 3	47.1 N	153.0 E	15	27	03	150 ±	Kuriles
	September 25	0.5 N	127 E	23	31	10		
67	October 3	26 N	55 E	06	14	00		
68	October 3	16.9 N	99.4 W	08	11	08	50 ±	
69	October 3	18.6 N	101.5 W	23	32	15	100 ±	Southern Mexico
70	October 5	4.0 S	133.7 E	18	40	42		
71	October 6	36.9 N	21.7 E	19	55	40		
72	October 7	64.0 N	148.6 W	01	53	23		
	Aftershock			02	57	30		
73	October 10	44.3 N	145.9 E	07	32	47	300 ±	Kuriles
74	October 10	31.0 S	177.8 W	13	42	52	100 ±	Kermadec Island
75	October 14	32.8 S	178.4 W	01	41	14		
76	October 16	63.8 N	148.1 W	02	09	50	50 ±	
77	October 20	64.0 N	147.9 W	01	43	17		
78	Supplement for October contains:							
	October 1	12.2 S	166.1 E	12	31	40	100 ±	New Hebrides
79	November 1	6 S	102 E	05	59	33		Deep?
80	November 1	10.8 S	74.5 W	14	58	54		Deep?
81	November 2	40.6 N	126.5 W	07	00	26		
82	November 4	44.8 N	139.6 E	00	09	14		
83	November 7	10.8 S	74.5 W	23	00	29		Deep?
84	November 8	1.7 N	82.5 W	05	25	30	200 ±	West of Ecuador
85	November 9	23.4 S	170.4 E	04	57	51		
86	November 12	30 N	113.5 W	01	39	55		
87	November 12	23.5 S	170.5 E	16	18	58		
88	November 14	44.3 N	143.6 E	10	50	30	200 ±	East of Hokkaido
89	November 17	17 N	46.3 W	09	56	51		
90	November 18	33.2 N	119.3 W	21	59	07		
91	November 20	48.8 N	154.8 E	08	19	48	130 ±	Kuriles
92	November 21	19 N	107.3 W	03	54	15		
	Aftershock			04	17	39		
93	November 23	44°54'N	111°43'W	09	46	05		
94	November 25	10.8 S	74.5 W	18	15	10	50 ±	
95	Supplement for November contains:							
	November 12	24.0 S	170.8 E	10	39	12		
	November 15	53.8 N	162.6 W	20	22	23	50	
	November 21	5.8 S	152.1 E	19	02	06		
96	December 14	27 S	63 W	02	16	15	100 ±	Argentina
97	December 15	60.3 S	166.8 W	19	20	17	100 ±	South Pacific Ocean
98	December 16	30.5 N	114 W	11	26	52		
99	December 23	15 N	92 W	01	56	08	100 ±	South Pacific Ocean
100	December 24	54 S	110 E	05	21	48		
101	December 24	15.0 N	98.2 E	16	36	38		
	Aftershock			17	36	28		
102	December 26	20 S	169.7 E	16	44	02		
103	December 30	9.5 N	84.0 W	01	55	18	50 ±	
104	December 31	16 S	173.4 W	15	06	36	60 ±	
105	Supplement for December contains:							
	December 21	20 S	160 W	16	46	13		

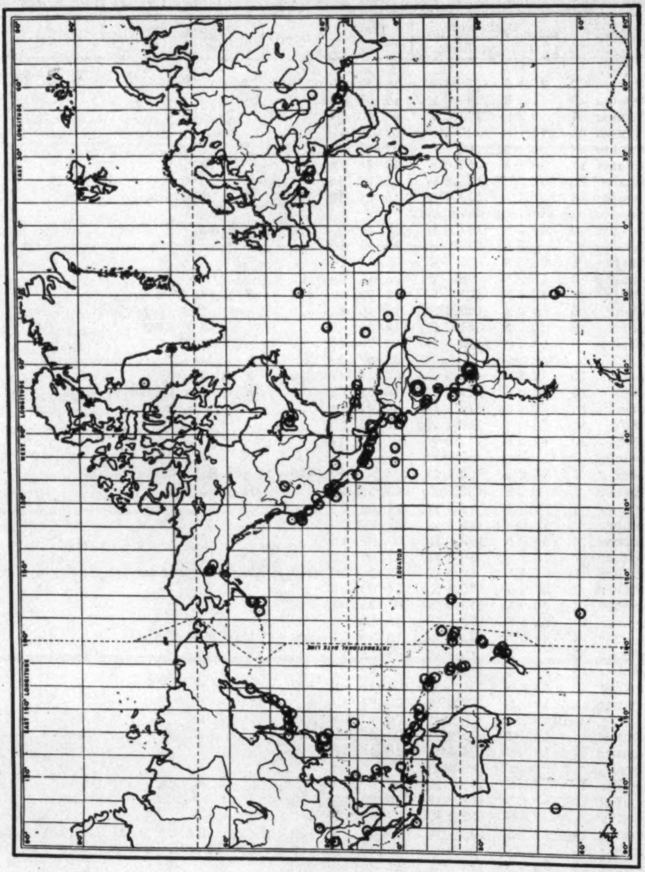

Fig. 1--Map showing locations of epicenters

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(Manuscript received June 18, 1948; presented at the Twenty-Ninth Annual Meeting, Washington, D. C., April 23, 1948; open for formal discussion until July 1, 1949.)

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REPORT OF COMMITTEE ON EVAPORATION AND TRANSPIRATION, 1947-1948

H. G. Wilm, Chairman

E. A. Colman
A. Russell Croft
C. Warren Thornthwaite
Marvin D. Hoover
Harold J. Lutz
Joseph Kittredge
Benjamin Holzman
Luna B. Leopold
Harold C. Troxell

For this report it was suggested that, if the committee members did not have current research progress to report, they might contribute their comments on the following topic: Gains in water content of soil or snow during rainless periods. The results are presented below.

Joseph Kittredge (School of Forestry, University of California, Berkeley, California)--In some localities where fogs are prevalent, drip from the trees may be an important source of water for the soil when no precipitation is recorded in rain gage in a standard exposure. An outstanding example comes from the Cascade Head Field Station of the Pacific Northwest Forest Experiment Station, which is located close to the Oregon coast. During an aggregate of 142 foggy days, when the precipitation recorded in a standard gage amounted to 25.19 inches, the average of the catch in three gages under a dense stand of sitka spruce and western hemlock 150 ft high, amounted to 36.42 inches. The excess of 11.23 inches, or 0.08 inch per day, resulted from fog drip from the trees.

Condensation as a source of moisture to the soil has been well demonstrated by the weighing lysimeters of the Soil Conservation Service at Coshocton, Ohio [HARROLD and DREIBELBIS, 1945]. Dew and frost deposited on these grass-covered lysimeters amounted to four or five inches depth of water annually. The maximum in any one month was 1.10 inches in January or more than 0.03 inch per day.

Table 1 provides an example of increases in soil moisture frequently recorded in periodic samplings during rainless periods in a denuded clay loam soil on a 40 per cent southeast exposure from April 29 to May 1, 1939 in the hills east of Berkeley, California.

Table 1--Soil-moisture increase during rainless period, April 29 to May 1, 1939, near Berkeley, California

Depth sampled	Moisture		Change	Volume weight	Change
	April 29	May 1			
in	pct	pct	pct		in/24 hr
0-2	6.29	11.23	+ 4.94	0.99	+ 0.047
2-4	19.41	20.78	+ 1.37	0.99	+ 0.013
4-6	21.55	27.01	+ 5.46	1.02	+ 0.053
6-8	21.54	23.42	+ 1.88	1.025	+ 0.018
8-10	22.77	23.36	+ 0.59	1.00	+ 0.003
0-10	....	....	.....	....	+ 0.134
10-12	24.49	21.86	- 2.63	1.00	- 0.029
12-14	24.74	22.95	- 1.79	0.99	- 0.050
10-14	....	....	.....	....	- 0.079

Recognizing variations in moisture content attributable to local differences in the soil, there can be little doubt that the increases in moisture content in the upper ten inches during these two days were real and in contrast to the decreases in the 10- 14-inch depth and in the preceding and subsequent periods. During still, clear nights when the soil surface is strongly cooled by outgoing radiation, the temperature at the surface is likely to be considerably lower than that of the air above or of the soil several inches beneath the surface. Thus the pressure gradients of water vapor are toward the surface both from the air and from the deeper layers of the soil. Under these conditions both condensation from the air and vapor movement upward from the deeper layers of the soil will take place. In the foregoing figures a part of the increase in the 0-2-inch layer might be ascribed to condensation, but it seems quite unlikely that dew would be sufficient to increase the soil moisture to depths between four and ten inches. Moreover, the noticeable reduction in moisture content of the 10- 14-inch layer suggests withdrawal of moisture from that layer into the overlying layers. An increase of more than 0.13 inch per 24 hours is a considerable change in moisture content. It would be interesting to know what the upper limits of the amount of water which may move in this way, might be.

Alternate freezing and thawing of the surface layer of the soil drew more than 0.5 inch of water in ten days from the 30- 36-inch depth to the surface at North Fork, California, even when the whole soil profile was well below field-moisture capacity [ANDERSON, 1946]. This may be an important source of surface water drawn from considerable depths in the many places where freezing and thawing at certain seasons are frequent phenomena. Alternate freezing and thawing is also characteristic of snow layers during the melting period, and the possibility may be suggested that the large increases in water content of snow frequently indicated by successive samplings with snow tubes may be the result of water drawn from the underlying soil up into the snow layer in response to the forces of crystallization.

H. J. Lutz (School of Forestry, Yale University, New Haven, Connecticut)--The following abstracts of papers may be of historical interest on the subject of gains in soil water content:

Kessler, Paul, Ueber Enstehung von Wasser in Boden und Gestein durch Kondensation, Forstliche Wochenschrift Silva, v. 10, pp. 193-198, 1922: At a meeting of the German Society of Engineers held in Frankfurt am Main in 1877 Otto Bolger, an outstanding worker in the field of water relations advanced the view that "Kein Wasser des Erdbodens ruhrt her vom Regenwasser." He held that the ground water was derived from condensation in the soil of atmospheric water vapor. Kessler remarks that the idea of Volger was not new, similar views having been expressed by Aristotle and Seneca. Volger was opposed in his extreme view by the meteorologist Hann and the soil scientist Wollny. In the opinion of Kessler the positions of both Volger and Wollny were extreme and not justified. Addition to soil water through condensation of atmospheric water vapor is probably most important in regions of arid climate.

Weise, Ueber den Einfluss der Bodentemperatur auf die Feuchtigkeit der oberen Bodenschichten, Mundener forstliche, v. 5, pp. 81-91, 1894: Weise emphasized the significance of the upward movement of water vapor from the deeper, warmer soil layers to the colder surface layers of the soil in the fall and winter. As the vapor is condensed in the surface layers it freezes, thus accumulating. Weise mentioned a simple experiment for demonstrating this phenomenon. Long glass tubes with one end bent to form an arm were inserted vertically in the soil. Water vapor moving up from the deeper soil layer was said to condense in the arm at the surface and in weather with freezing temperatures ice accumulated in the arm at the surface.

Chaptal, L., Dew and aqueous deposits from the air (translated title), Ann. Sci. Agron. Franc. et Etrang., v. 47, pp. 69-77, 1930. Experiments are reported which confirm previous conclusions that absorption of aqueous vapor from the air by the soil as distinguished from dew deposition is a general and important phenomenon in hot seasons in southern France. The apparatus and method used for distinguishing between the two sources of moisture are described. (Note: The above is cited from Experiment Station Record, v. 65, p. 111, 1931; the original was not seen.)

H. G. Wilm (Southern Forest Experiment Station, New Orleans, Louisiana)--During the period 1940 to 1944, the Rocky Mountain Forest and Range Experiment Station made a series of attempts to work out methods for measuring evaporation and sublimation of water from stored snow. Most of these experiments were concentrated on a set of round metal pans, the largest of which was 500 sq ft in area. For the larger pans, changes in water were estimated by the combination of several kinds of measurement: (1) Precipitation during the winter and spring, through the use of four standard rain gages with Alter shields and one Friez reconnaissance recording rain and snow gage. These measurements may contain some bias due to the failure of any gage of this type, even though shielded, to catch the true total precipitation. (2) Water content of snow at five-day intervals, through samples taken with Utah snow tubes and other samplers on 11 snowboards surrounding the largest pan. These measurements were subject to some bias due to the failure of the snow tubes to obtain a true sample of water content, as well as to the fact that no samples could be taken directly on the pans but had to be on adjacent land. They are also subject to sampling errors, associated with variations in water content of snow from point to point over the area. (3) Runoff of water from the melting of snow on the pans. No sampling error could be associated with these measurements, as all of the runoff was measured; but there may be some bias if there was any migration of water along snow crusts within the column of snow over the pans. If such migration occurred, the amounts of water reaching the collector cans might have been more or less than the true amount of water melted from the snow directly over the pans.

Estimates of snow evaporation or sublimation were obtained by subtracting the runoff per five-day period from the amount of water which should be expected to appear as runoff during that time: Snow water content at the start of the period, plus precipitation during the period, minus snow-water content at the end. Expressed as an equation, $E = (S_1 + P - S_2) - Q$.

When this equation is studied in the light of the various errors and biases which are necessarily (at this stage in our methodology) associated with the estimation of each of its terms, it is evident that figures on evaporation may be characterized by a good deal of variation which is due purely to these errors and biases.

In a series of 11 figures on five-day evaporation totals obtained during the spring of 1941, the indicated evaporation varied from -1.10 to +0.95 inch with an average of 0.25 inch, or about 0.05 inch per day. The five negative estimates which were obtained (-1.10, -0.17, -0.58, -0.04, and -0.59 inch) were well scattered, from March into May. Ordinarily these would be considered to provide estimates of condensation, during periods when measured precipitation did not show the total amount of water being added to the stored snow. This may be true, at least in part. It is also believed, however, that an unknown portion of each negative value, as well as of all the other estimates, must be charged to the effect of sampling errors and biases.

In addition to these contributions to the proposed discussion topic, the following comments were received on current research.

E. A. Colman (California Forest and Range Experiment Station, Berkeley, California)--With P. B. Rowe, a paper is being prepared on the soil-moisture studies conducted at North Fork and Bass Lake, California, and on the San Dimas Experimental Forest. The analysis of these data will permit a number of useful comparisons. First, we can compare evapotranspiration and seepage between several kinds of natural vegetation in the Sierra Nevada and the San Gabriel mountains. Second, we can study the effects of burning and denudation upon these processes at the several locations. Third, we can relate the findings of an extensive soil water-storage study to stream flow from a chaparral-covered watershed. It is hoped that this paper will be completed in manuscript within the next few months.

Along with this work, the finishing touches have been placed, at least for the time being, on our soil-moisture instrument. The redesigned soil unit is enclosed in a pressed monel metal case, and the wire-wound resistance thermometer has been replaced by a Western Electric Company thermistor. These changes have given improved stability of calibration and better possibilities for precision mass production.

Harold C. Troxell (Geological Survey, Los Angeles, California)--My association with evapotranspiration during the last five years has been through a report now in preparation on Hydrology of the San Bernardino and eastern San Gabriel Mountains. The evapotranspiration has been extimated largely by statistical methods.

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DISCUSSION OF

"EVALUATION OF SEA-SURFACE ROUGHNESS FROM UNDERWATER-PRESSURE RECORDINGS" by H. R. SEIWELL

[Trans., v. 29, pp. 197-201, 1948]

J. W. Johnson (University of California, Berkeley, California)--Under the discussion of wave period, the author states, "Periods of surface waves are to be expected to be lower than those recorded at or near the bottom." This statement is true, but it should be supplemented by a statement to the effect that, by placing a pressure pick-up unit below the sea surface, pressure fluctuations due to the shorter period waves are inappreciable or non-existent because of hydrodynamic filtering. Thus, only the pressure fluctuations from the longer period waves are present to activate an underwater pressure pick-up unit. The relationships between the period of subsurface pressure-fluctuations and the average period of the combined wind waves and swell observed at the surface given by the author for stations at Cuttyhunk and Bermuda were merely a function of the depth of the instruments and the wind waves and swell that existed at the time of the observations. With different depths of instrument and different wave conditions, the filtering effects would be different; hence the ratio of periods as observed at the surface and recorded by an underwater instrument would be different. Without explanatory supplementary statements on filtering action accompanying wave motion, it is believed that the casual reader would be led to the erroneous belief that a certain single wave train would have a different period whether observed at the surface or below the surface.

What appears to be an oversight in proofreading is the fact that the sentence, "On the basis of simultaneous surface and near-bottom observations in 1946, it was estimated that at depth of instrumentation, the average period of Cuttyhunk was about one-half that occurring at the surface, and at Bermuda about one-third," contradicts the sentence previously quoted. The meaning of this last quoted sentence can be made correct by substituting the word frequency for the word period, or by changing the word one-half to read two and the word one-third to read three.

H. R. Seiwell (Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, Author's closure)--The paper discussed by Johnson was a condensation of certain results of wave research then in process of detailed publication [SEIWELL, 1948]. The preliminary paper was a brief of new results obtained by a statistical approach to the general wave problem. For details the reader is referred to the larger paper indicated.

Reference

SEIWELL, H. R., Results of research on surface waves of the western North Atlantic, Papers in Physical Oceanography and Meteorology, v. 10, no. 4, 56 pp., 1948.

DISCUSSION OF

"REPORT OF THE SUBCOMMITTEE ON SEDIMENT TERMINOLOGY"

E. W. LANE, Chairman

[Trans., v. 28, pp. 936-938, 1947]

Robert F. Legget and **F. Lionel Peckover** (Division of Building Research, National Research Council, Ottawa, Canada)--This report will be welcomed by all working in the field of sediments as clarifying terms for general benefit. This proper use of the international influence of the American Geophysical Union should ensure consideration of the recommendations in all English-speaking countries.

The report notes, "the recommendation of great changes in the customary terminology would not be accepted by workers in the field, and therefore would not produce the desired results."

This principle, fundamental in the presentation of such a report as this, has been followed throughout, with one important exception which will be discussed in detail below.

In particular, the report commendably avoids the use of the word classification, commonly misleading when applied to sediments and soils. These materials can never be classified by any means less than a thorough investigation of their important physical properties. However, the belief is common that such a classification can be made on the basis of grain size alone. The word classification in itself gives the impression that any soil or sediment may be put in a definate pigeon hole with a label such as sandy silt or clay and expected to have the physical properties implied by such names. Those dealing frequently with soils will know the fallacies of such assumptions. The term classification, therefore, should properly be applied only to such groups as those into which the range of grain sizes may be divided.

As has already been mentioned, there is, in the opinion of the writers, an important exception in this report to the axiom that suggested standards should be kept as much in line with accepted practice as possible. This exception is the recommended grade scale of size terms for sediments, given in Tables 1 and 2 on page 937, and the remainder of this discussion will deal exclusively with this recommendation. Grade scales of particle or grain size originated in various attempts to group particles of soils and sediments within certain size limits. The resulting groups are called fractions or grades. Some of the numerous systems of this sort now recognized and in use are shown in Figure 1. These groups are convenient since descriptive words convey more to the average person than do actual dimensions. Unfortunately however, different systems have never been correlated and few definitions in technical work are so confused and confusing as those for the grain size of soils and sediments. Hence, the use of descriptive group names, if they are to be specific and of practical use, must always be supplemented by a statement of the system used. For example, fine sand of the Continental system may have quite a different composition to that of the International system, the former being composed predominantly of grains ranging from 0.1 to 0.2 mm, and the latter from 0.02 to 0.2 mm. CASAGRANDE [1947] has recently discussed various grain-size scales.

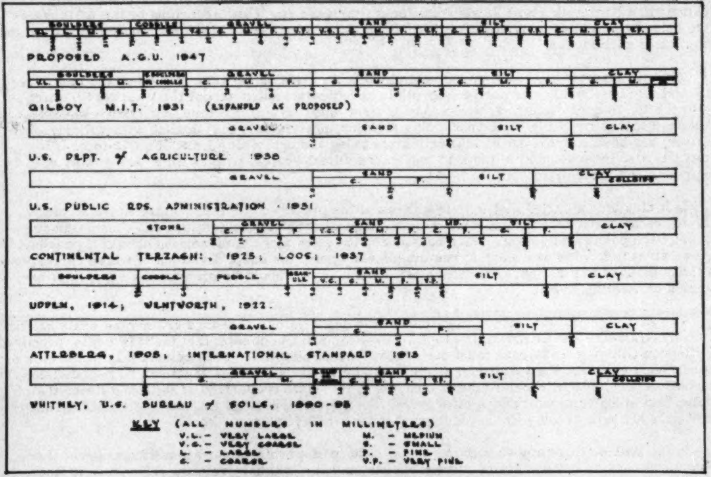

Fig. 1--Comparison of principal grain-size scales

All subdivisions in such scales are arbitrary since a continuous series is involved; but their usefulness is beyond question and they form a part of the general knowledge of geologists, soil scientists, civil engineers, and many others. It is because of the widespread use of these groupings that the adoption of a particular system for general application would be desirable. If a system could be found to perform satisfactorily in all fields concerned, all would benefit accordingly and valuable interchange of data would be facilitated.

Any standard suggested for adoption, whether in one field or many, should be either already recognized and used fairly widely, or evidently much superior to any other now in use. The grain-size scale for sediments proposed in this report of the Subcommittee on Sediment Terminology fails to meet either of these criteria, in the opinion of the writers. The only recognized scale to which it bears some resemblance is that of Wentworth (see Fig. 1), sometimes used by geologists. However, it differs somewhat from this and must therefore take its place as the most recent addition to the already lengthy list of its predecessors.

Apart from its originality, the virtues of this new system are open to question. The simple geometric progression of its size fractions and consequent uniform divisions on a logarithmic scale make it easier to remember and neater in appearance than some other systems, although difficult to plot accurately. It is undoubtedly one of the most complete (and correspondingly complex) grain-size scales ever assembled, as will be seen by comparison of the number and size of its subdivisions with those of other systems. This complexity, while allowing the use of additional descriptive terms, raises very real doubt as to its field application and hence its adoption for general and practical use. In addition, when such divisions are so limited in range, the majority of sediments are predominantly composed of grains falling into more than one division of the scale. This brings up the question of justification for such a thorough subdivision. The necessity of describing a border line soil as very coarse silt or very fine sand according to the AGU grain-size scale seems to destroy some of the natural simplicity and clarity which originally led to the adoption of such scales.

A final comment on the proposed scale is that its division between silt sizes and clay sizes at 0.004 mm does not correspond to any other accepted standard except the Wentworth, which is quite limited in use. This fact, which may at first seem trivial, gathers importance when it is explained that most of the work on the clay fraction, particularly that dealing with colloidal properties, has been carried out by soil scientists using the upper size limit of 0.002 mm. This limit has also been adopted in the MIT and International scales, both of which are widely used by engineers and agriculturalists.

If it may be concluded that the advantages of the proposed AGU grain-size scale do not justify its recommendation for general adoption, what alternative suggestions can then be made? As has been pointed out, a size scale considered for such a recommendation should if possible be one already in wide use, easy to remember and apply, the basic divisions of which correspond to those most widely recognized. Above all, such a scale should be simple, and capable of expansion to meet all needs.

The most careful consideration to date of the question of a standard grain-size scale has been given by GLOSSOP and SKEMPTON [1945]. They formed the opinion that the MIT scale, proposed by Glennon Gilboy in 1930, was most suited for general adoption. This opinion was based on a detailed investigation of the validity of distinctions between the various fractions and subdivisions thereof, particularly with reference to changes in the basic properties of soils and hence their application in experimental and applied work. As a direct result of this paper, the MIT grain-size scale has now become the recognized standard in British soils work.

In the United States and Canada, no such trend to one scale is yet apparent and several are in common use. In spite of its relatively recent introduction, however, the MIT scale is finding widespread use in the engineering field and has gained recognition in others. A close examination of this scale and comparison of it with the proposed AGU scale may indicate its suitability for other fields.

In Figure 1, it is seen to have the same advantages of the AGU scale in uniformity of divisions. These, however, are not so numerous in the MIT system and permit the simple breakdown of each size fraction into coarse, medium, and fine material. The scale can be (and is) expanded in each direction as far as required. This arrangement should be ample for most purposes.

Another mutual advantage of both scales is the ease with which their size divisions may be remembered, although it is suggested that those to whom mental arithmetic is painful may prefer the simple two-six repetitional pattern of the MIT progression. The numbers of the latter also, being rounded, simplify accurate plotting of the chart. Another advantage is that the necessity of converting from fractions to decimals, evident in the AGU scale on page 937, is avoided.

The joint use of fractions and decimals, for example, 1/32 mm or 0.031 mm) causes confusion by intermixing English and metric concepts, and strict adherence to the metric system is advisable, particularly if the scale is to have wide application.

More important are the main divisions of the MIT scale. The gravel-sand size has already been standardized; the sand-silt size has been found by Glossop and Skempton to correspond to important changes in the physical properties of soils; and the silt-clay size, as already mentioned, corresponds to that widely used in scientific work. Moreover, in the instances investigated, these fractions have been found to agree satisfactorily with well-known local deposits to which names have been given, such as Chicago Clay and Daytona Beach sand.

Most important in a consideration of the MIT scale is the fact that it is simple, and already in wide, satisfactory, and increasing use in many countries. At this date it provides the most hopeful prospect of a standard grain-size scale for sediments.

In view of these facts, the writers respectfully make the recommendation that consideration be given by the Subcommittee on Sediment Terminology to the adoption of the MIT grain-size scale in order to (1) avoid the further confusion in this field which would result from the addition of a new scale; (2) make a step toward standardization and conformity on an international plane, in keeping with the widespread prestige which the AGU enjoys in many aspects of science; and (3) provide a closer link with the broad fields of soil mechanics and soil physics, as of increasing general use in applications of sediment studies.

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Walter T. Wilson (44 Loma Road, Redwood City, California)--The Committee deserves much credit in recognizing the need for, and doing something about establishment of standard terminology. Being neither a sedimentation expert nor a lexicographer, perhaps I am dashing in where angels fear to tread. However, in my frequent reference to a dictionary, and in studying the introductory portions of my unabridged dictionary, I have concluded that a dictionary does not present decisions involving the necessarily correct or exclusive use of words as much as it summarizes accepted use. The process of compiling a dictionary seems to involve collecting and then summarizing examples of uses of words, thus being historical and descriptive instead of critical. For technical terms, lexicographers search the writings of recognized authorities, professional committees, and others. Therefore a committee of experts referring to a dictionary may give the impression that its members have modestly and politely abdicated their responsibility.

The quoted definition of sediment seems to be inadequate, in that it fails to exclude glacial material. The question is raised: Are round stones fragments? This Subcommittee seems to be associated with the Committee on Stream Dynamics, and the subject matter is largely in this field. However, the definition chosen includes airborne material, deliberately or otherwise. If this Subcommittee regards airborne material as within its scope, the report appears to be incomplete.

In the definition of suspended load, the distinction between colloidal and turbulent suspension is significant but undefined.

Another criticism is the dual definition of suspended load on the basis of a distinction between a total element and samples of it. This problem appears throughout hydrology, with other examples being precipitation, water equivalent of snow on the ground, wind speed, and soil moisture. The fundamental element from which samples are abstracted is no more true than the observed samples. In fact the word true begs an operational definition except by observing samples.

One more criticism concerns the table of scale of sizes. Unfortunately there are in established use many such tables, all different, and it is extremely doubtful if all the soils men, physicists, engineers, and other workers who use measurements of mineral particles will ever agree on arbitrary class limits and corresponding adjectives. Further, I see no need for it. I would hesitate to memorize such a table, with 24 adjectives, and I doubt if I could depend on having a printed table conveniently at my elbow whenever I might need it. I would much rather use basic numerical terms in describing or estimating the size or sizes of material than start with a number, look up the correct word for it, use the word, and have my reader or listener translate the word back to the correct number to know what I am talking about. It would be convenient to speak of material ranging from 0.1 to 1.5 mm, with a median size of 0.4, rather than describe it as fine sand, very fine sand, or coarse sand, and then have the question of whose sand it is: that of the Sediment Subcommittee, the United States Department of Agriculture, the International Society of Soil Science, or some other authority.

Being aware of the impossibility of a report such as this pleasing all readers or critics, perhaps not even all the committee members, I do not mean to labor this Subcommittee as much as to take advantage of this opportunity to stimulate critical thought along lines which apply rather generally to problems of terminology.

E. W. Lane (2572 Dahlia St., Denver, Colorado, Chairman's closure)--The Subcommittee on Sediment Terminology adopted the definition from the New Standard Dictionary because it seemed to be as good a definition as any which could be suggested, and therefore there was no point in making up another one. For the purposes of this Committee it was not necessary to include airborne material or material deposited in bed by other natural agents (such as glaciers), but the inclusion of them makes the definition acceptable for general geology as well as to geologists and engineers interested in the more narrow field of stream dynamics.

Part of the objection to the proposed classification appears to arise from insufficient contact with the use of size classification between the soil mechanics and the sedimentation field. It might have been better to have expanded the report somewhat by giving the background of the size classification adopted.

UDDEN [1898] proposed size classification extending from 16 mm to 1/256 mm in which the lower limit of each size was half that of the upper limit. He extended it [UDDEN, 1914] from 256 mm to 1/2048 mm. His larger sizes did not conform very well to the ideas of geologists and WENTWORTH [1922], after canvassing a large number of geologists, brought out his scale, which has the same division points between classes as Uddens and in many cases the same names for classes, but did not subdivide clay, silt, or boulders. His classifications of granule and pebble between two and 64 mm did not meet with general acceptance, although his scale in general became widely used by geologists. In his studies of the Missouri River sediments, STRAUB [1935] combined the Udden silt classification with the Wentworth classification and added the word gravel to Wentworth's descriptive terms for sizes above two mm. The classification proposed by this Committee has adopted Udden's subdivisions for sizes up to one mm. Wentworth's from one to two mm, has modified Straub's classification between two and 64 mm by dropping the terms granule and pebbles introduced by Wentworth, and subdivided the cobble and boulder classifications of Wentworth. It will thus be seen that this classification is not a new one, but rather the product of an evolution started by Udden in 1898, with contributions by Wentworth and Straub and some additions by this Committee, each step being a perfecting in some degree of the previous steps.

The classification labeled Udden-Wentworth on Legget and Peckover's diagram is incorrect as it is the Wentworth classification only. If they had subdivided the silts and clays as Udden proposed, it would differ from the proposed AGU classification only between two and 64 mm, and in the subdivision of cobbles and boulders.

The Udden-Wentworth classification is not a seldom used classification, as the Legget-Peckover discussion seems to indicate, as it has been extensively used by geologists, in the Missouri River studies previously mentioned, and in extensive work by the Sedimentation Section of the Soil Conservation Service. Practically the same classification has been used for sediment work in India. The AGU classification is also coming into extensive use in this country, having been adopted by the United States Bureau of Reclamation for their sediment studies and is also likely to be adopted by the other Government agencies active in the sediment field. It is therefore not improbable that the AGU classification will be more generally used in the sediment field than the MIT classification is used in the soil mechanics field.

No size classification is ideal, all have their superior points and their weaknesses. Legget and Peckover bring out the good points of the MIT classification but do not discuss its disadvantages. One of these is that since the spacing of the divisions on logarithmic paper is not exactly equal, it cannot be used in the statistical methods which have come into wide use in analyzing sediments in the geological field. Another is that the MIT method of subdivision is not the same throughout as the Legget-Peckover discussion states as the boulder classification differs from the others.

Because the quantity of sediment transported is highly sensitive to size, it is necessary to have a large number of classes to give sufficiently fine definition to be satisfactory. The classes of the MIT classification, being 67 per cent larger than those of the AGU classification are considerably less advantageous for sediment work.

Since size classifications are becoming of less importance in the soil mechanics field, but are likely to be very important in the sediment field for a long time to come, it would seem more logical, if any single classification is to be adopted, that it be the one best adapted to the field of greatest interest, and hence that the AGU classification be generally adopted rather than the MIT. Actually however, the MIT and AGU classifications are very similar, since, except for the silt-clay division point, all the major size-division points are very nearly the same, and the disadvantages of using one in the soil mechanics field and the other in the sediment field are not very great.

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Carl B. Brown (Soil Conservation Service, Washington 25, D. C., Closure by a Committee member)--Leggett and Peckover recommend the adoption of the MIT grain-size scale in lieu of that proposed by the Subcommittee, in order, they say, to "avoid further confusion," to promote "standardization," and to provide a closer link between sediment and soils studies.

Arguments for adoption of a "standard" grade scale can be traced through the soils, geological, and engineering literature for the last 30 years. The existing multiplicity of scales would indeed be deplorable, if the different grade scales were used for the same purpose in agricultural soils, soil mechanics, sedimentary petrology, and stream-dynamics investigations. The situation would be comparable to the use of different screw-thread specifications by the British and Americans which is just now, after 30 years of argument, being resolved. In the present case, however, the principal needs for and uses of grade scales in these respective fields differ quite significantly.

In the opinion of the writer, it is neither practicable nor desirable to attempt to obtain the adoption of a single scale in all of the pertinent branches of science. Such an attempt would be like trying to standardize on a single lens prescription for all defective eyes regardless of individual requirements; and therefore unlike the case of screw threads which serve the same purpose no matter what the size of the screw. For example, in agricultural soil science grade scales are used primarily (1) for descriptive purposes, that is, in connection with classifying the soil type, such as a fine sandy loam, and (2) to give a partial measure of permeability and response of the soil to fertilization, tillage, erosion, and other factors, by correlation of mean size or quantities with measured responses of the soil. It has long been recognized, however, that many factors other than particle size-frequency are important and often dominant in the response of the soil to management. In the light of 50 years' accumulation of soils analyses based on the United States Bureau of Soils or USDA scales, it would surely appear inadvisable to try to induce agricultural soil scientists to adopt the recommended scale. Moreover, the AGU scale has an entirely unnecessary number of sub-divisions for agricultural use, and some sub-divisions may be at the wrong place with respect to certain inherent soil properties; for example, the division between silt and clay. On the other hand, the United States Bureau of Soils and USDA scales have proved unsuitable for many statistical studies of sediment transportation in streams. Because so many analyses of sediment are currently reported on these and other scales, it has been necessary to do a great deal of work in plotting them on suitable graph paper so that frequency values can be interpolated at intervals that will give a geometric progression suitable to statistical treatment by moment measures.

Workers in soil mechanics long ago became dissatisfied with the agricultural soil scientists' scales and largely developed and adopted the MIT scale. From a descriptive standpoint this scale could be used for sediment-transportation studies just as well as the AGU scale or the USDA scale.

The practical difference for such a purpose is very slight. But for statistical use, and particularly to obtain a sufficient number of class intervals to reflect the delicate balance between size, settling rate, and hydraulic forces of transportation, the data must be plotted and interpolated. Moreover, it appears from the article by Casagrande (p. 787), cited by Leggett and Peckover, that in the field of soil mechanics, "Because of the limited usefulness of the grain-size scales, the lack of a uniform standard is less serious than would be expected. Since the new USDA scale is almost identical with the MIT scale, either would probably cause less confusion if adopted as a United States standard. In the absence of such a uniform standard, it is desirable to adhere to the designation of the numerical limits of the grain-size fraction, omitting any names for the individual fractions."

As far as the writer is aware, it was never the intention of the Subcommittee to recommend this scale to other than those working in the field of sediment transportation. On the other hand, there are several compelling reasons why soils laboratories, which are currently making most of the sediment analyses, should recognize the distinctness of the rapidly expanding field of sediment studies; and concede to its requirements in both the analysis and reporting of textural data.

Special Announcements

Thirtieth Annual Meeting, Washington, D. C., April 20 to 22, 1949--Pursuant to the preliminary earlier announcement of the Thirtieth Annual Meeting of the American Geophysical Union on April 20 to 22, 1948 (Wednesday to Friday), arrangements are under way to provide sessions for all Sections, as well as a general session, and joint sessions of two or more Sections. Place this on your agenda and make plans to come.

This announcement is also an invitation for members and others to communicate plans for preparation and presentation of papers. Titles of papers with three copies of the abstract should be sent in at the earliest possible date, and not later than March 7, 1949, advising of the time required (most papers are allowed from ten to 20 minutes) and projection equipment needed. Send abstracts to the office of AGU at 1530 P Street, N. W., Washington 5, D. C., or to the Secretary of the appropriate section listed in the Transactions of December 1948, p. 948.

Complete manuscripts of papers should be forwarded in triplicate by March 31, 1949, in order that news releases may be prepared. If a paper is written in collaboration, please indicate by whom it will be presented. Arrangements can be made for presentation of papers by authors who are unable to attend the meetings. Advise also whether the paper is being submitted for the program only or whether it is also desired that it be given consideration for publication. (Papers for publication only are also welcome for consideration for the Transactions. See pp. 159-160 of this issue for suggestions to authors.)

The Chairman of the Committee on Meetings (J. P. Marble, U. S. National Museum, Washington 25, D. C.) invites suggestions and comments that will be helpful in planning the proposed meeting. Especially invited are comments relating to papers and symposia bearing on more than one section.

Make hotel or room reservations directly with the hotel of your choice as soon as possible. Failing on a first attempt, bear in mind that advance bookings not taken up are cancelled two weeks in advance, so a follow-up request in the opening days of April may bring the desired response. Our meeting is scheduled for the same week as the convention of the DAR in Washington. This has been true for the last two years also, but at no time yet, to our knowledge, has it not been possible to find quarters. Even though no advance reservation has been made, it has been possible to arrange for quarters after arrival in Washington through the Greater National Capital Committee (204 Evening Star Building, Washington 4, D. C., telephone DIstrict 3535) but they may find it necessary to direct you to a tourist home.

Twenty-Fourth Regional Meeting in Denver, April 26 and 27, 1949--The Twenty-Fourth Regional Meeting will be held in Denver, Colorado, April 26 and 27, 1949, jointly with the Western Snow Conference. While the AGU meeting will be essentially one of the Section of Hydrology, related papers will be welcome. The meeting on April 26 will be that of the Western Snow Conference, and on April 27 that of the Section of Hydrology. Persons interested in taking part in the meeting should write to Herbert S. Riesbol, Bureau of Reclamation, Denver, Colorado, in charge of arrangements for the Section of Hydrology, or Ralph L. Parshall, Ft. Collins, Colorado, General Chairman of the Western Snow Conference, in charge for the Western Snow Conference.

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REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

SHEPARD, FRANCIS P., Submarine geology, Harper and Bros., New York, 348 pp. + 106 figs. + 1 map + index, 1948.

Commencing with the history of marine geology and with methods of exploring the ocean floor, the author next discusses waves and currents and shoreline classification. This leads logically to consideration of shifting sand and beaches alongshore. Then continental shelves, continental slopes, and the floor of the deep oceans are treated; submarine canyons and coral reefs each has a chapter.

Shepard's researches in recent years have been largely devoted to submarine canyons. In discussing the various hypotheses of their origin, he eliminates all but sub-aerial erosion when sea level was 2000 ft lower than at present, with the missing water tied up in polar ice caps. The geochemical and biological question that is a necessary consequence of this hypothesis--What happened to the salt?--is not mentioned.

A refreshingly casual and iconoclastic style characterizes the book. The author is a strong believer in string and baling wire devices; he has little faith in the accuracy of some of the position determinations obtained by the United States Navy; and he even detects errors in recent surveys by the United States Coast and Geodetic Survey. More of this kind of skepticism is needed in other branches of geophysics.

JOHN LYMAN

HANSEN, G. J. A., and SVEISTRUP, P. P., Arctic ice fluctuations in Julianehaab Bay, 1901-1937, Med. Grønland, Kobenhavn, v. 131, no. 13, pp. 1-32 + 8 diag., 1943.

After a brief reference to the origin of the ice along the southwest Greenland coast, several factors of possible significance in its annual fluctuation are considered. Among these are (1) the March through November surface-water temperature (in the absence of sufficient winter observations) between the Shetland Islands and the Faroes (58°N to 62°N and 08°W to 06°W) taken as a measure of the North Atlantic warm water flowing into the Arctic; (2) the annual air temperature at Spitzbergen, Jan Mayen, Bear Island, and at Ingoya-Gjesvaer in northermost Norway as an indication of the severity of the temperature in the Arctic; (3) the annual wind direction at Grimsey, off the north coast of Iceland as a factor in the amount of ice drifting southwestward through Denmark Strait; and (4) the annual surface water temperature at Selvogsbanki immediately off the southwest coast of Iceland as a measure of the warm Irminger current flowing into Denmark Strait where it meets the ice bound for Cape Farewell and Julianehaab Bay.

Employing the ice values derived from the mean April-August limits published by the Danish Meteorological Institute, the authors correlated the temperature of the Arctic-flowing water in the Shetland-Faroes section with the ice of Julianehaab Bay the same year and also a year later. The obtained negative coefficient with the temperature of the water the year before suggests that higher water temperatures tend to be followed by less ice and lower temperatures by more ice a year later. Considering that it takes about a year for the ice from the Arctic drifting along the east coast of Greenland to reach southwest Greenland, the general trend of the indicated relationship is probably real.

The authors were not so fortunate in their attempt to link the annual air temperatures at Spitzbergen, and at the other stations to the ice off Julianehaab Bay. This is not surprising since they were comparing annual values on the one hand with five-monthly ice values on the other and thereby implying that the air temperatures in Spitzbergen, and the northermost Norway region are characterized by much persistence. Their use of annual or near annual water temperatures in the case before it should be remarked, appears entirely permissible in view of the marked persistence in the water temperature.

Next, assuming that north to southeast winds at Grimsey favor the southwestward drift of the ice along the East Greenland coast and winds from south to northwest favor the dispersal of the ice eastward, with the result that, less ice reaches the southwest coast off Greenland, the authors find many features in the wind curve in common with the ice curve off Julianehaab Bay especially for the first half of the period.

The rather poor agreement during the second half of the period is significant and does not in itself vitiate the apparent relationship for it can be rightly assumed that with on the whole much less ice in the years 1919-1936, the winds at Grimsey can have little bearing on the amount of ice drifting along the other side of Denmark Strait. Unfortunately, here again the authors' use of annual wind values would seem to have militated against obtaining a closer relationship.

The investigation of a possible connection between the ice off Julianehaab Bay and the annual water temperatures off southwest Iceland (Selvogsbanki) indicates a relationship with conditions a year later, much ice tending to be followed by lower temperatures and little ice by higher temperatures.

If the latter relationship is real it would be of much interest for it would mean that in some years either the East Greenland Polar Current is able to penetrate to the immediate vicinity off southwest Iceland and is not entirely stopped by the ridge running from northwest Iceland to Greenland or, what is probably more likely, the East Iceland Current turns westward after it has passed the east coast of Iceland to merge with the Irminger Current and somewhat to affect it.

IRVING I. SCHELL

NĚMEC, ALOIS, Geomechanics, the forces which form the Earth's surface, Prague, 2 vols., 215 and 48 pp., 1947.

Geology and its sister sciences are based on theories, some of which are little better than assumptions and guesses (such as, for example, Wegener's theory about the movement of continents). Up to the present, these theories have not been tested in the light of the generally accepted laws of mechanics. The author has made this attempt in his study and has sought to obtain important findings based on mathematics in harmony with the laws of mechanics.

His study applies the laws of mechanics to the conditions of the crust floating upon the liquid parts of our Earth and deals with the chief mechanical forces which by their effect upon the solid masses of the crust are shaping the surface of the Earth. He draws conclusions about the effects of these forces and points out that these effects are strongly supported by the actual conditions of the Earth's surface on the continents and under the oceans.

The author believes his conclusions to be in agreement with the actual conditions of the Earth's surface. This would be the best indication that the author's conclusions and findings are justified.

The author also believes that the findings arrived at are in agreement with the recent opinion on the permanence of continents and oceans and that they explain how the striking differences between the level of the continents and the bottom of the oceans originated.

A mathematical analysis of isostasy indicates that Pratt's isostasy does not explain the differences in the Earth's gravity on the seas, on the continents and in high mountains, although it attempts to do so. This book essays an explanation of these differences and their causes.

Explanations are offered for many phenomena including ocean currents, arrangement and assymmetry of continental sections, and the Atlantic Ridge and Pacific trenches.

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NOTES AND PERSONALIA

NOTES

Corrigenda--The following corrections are noted in the *Transactions*:

Vol. 29, October 1948, in the paper by J. Tuzo Wilson, p. 717, the right hand side of Figure 31 should be at the bottom to conform to the orientation of Figure 32 on the next page.

Vol. 29, December 1948, in the paper by P. D. Thomas, p. 763 in Equation (1) the last term of the denominator should be $\sin^2 \Delta\lambda$; also in this paper, p. 764, the beginning of the third (last) line of the third paragraph should read $= 6.7686580 \times 10^{-3}$.

Vol. 29, December 1948, in the paper by Ralph W. Powell, p. 882, about the middle of the fourth line in the paragraph headed *Development*, the equation should be $C^2k = V\,(2 - p)R^{\beta}$; also in this paper, p. 883, at the end of the first line under Equation (9), the differential should read $(dP/dy)/$; also in this paper, p. 885, the fifth column heading should read $F = 0.1781\,V/\sqrt{y}$.

Submarine-gravity expeditions in the Pacific-- The U. S. S. *Capitaine*, L. R. Vasey commanding, completed its gravity measuring cruise on December 1, 1948. C. L. Drake, observer, and J. G. Heacock, assistant, who joined the ship at Okinawa, observed 260 gravity stations every 50 miles along the route from San Diego to Pearl Harbor between the Ellice Islands and the Gilbert Islands, between the Santa Cruz Islands and the New Hebrides Islands to the west of Bampton Reefs to Brisbane, Australia, from Brisbane, Australia, to the west of Bampton Reefs to the east of the Louisiade Archipelago between Bougainville and New Britain, through the central Carolines to Guam, from Guam to Okinawa, from Okinawa to the north of Ogasaware Gunto to Pearl Harbor. In addition, ten stations at 20-mile intervals were obtained on each of five crossings of the earthquake epicenter belts. Preliminary reports indicate large negative anomalies on each of these crossings.

On December 5, 1948, the U. S. S. *Bergall*, S. L. Johnson commanding, left Pearl Harbor following a similar, but laterally displaced route to that of the U. S. S. *Capitaine*. J. G. Heacock, observer, and C. L. Drake, who left the ship at Brisbane, Australia, made the observations.

These expeditions have been arranged with the cooperation of the Office of Naval Research, Navy Department, and Commander Submarine Force, U. S. Pacific Fleet. The gravity observations were made with a Vening Meinesz pendulum apparatus and a Bell Telephone Laboratories crystal chronometer, loaned by the Woods Hole Oceanographic Institution. Additional observations of wave pressures were made with a sensitive pressure meter loaned by the Naval Ordnance Laboratory, to observe the relationship of wave motions to the disturbances of the pendulum apparatus. These observations further confirm the relation of the earthquake epicenter belts to the negative gravity anomaly strips.

This work is part of a two-year program of gravity observations at sea, sponsored by the Office of Naval Research. J. Lamar Worzel is in charge of the project, under the direction of Maurice Ewing of Columbia University.

Committee on Geophysics and Geography of Research and Development Board--W. E. Wrather, Director of the U. S. Geological Survey has been named Chairman of this Committee of the National Military Establishment. Samuel B. Morris, General Manager and Chief Engineer of the Department of Water and Power, City of Los Angeles, California; Horace R. Byers, Department of Meteorology, Chicago University; P. E. James, Department of Geography, Syracuse University; and Richard Joel Russell, Department of Geography, Lousiana State University are the other members. Helmut Landsberg has been named Executive Secretary of the Committee.

New edition of Physics of the Earth Series relating to Terrestrial Magnetism and Electricity, and Hydrology--A new edition of Physics of the Earth Series, Volume VIII, Terrestrial Magnetism and Electricity was published by Dover Publications, 1780 Broadway, New York 19, New York, February 15, 1949. A new edition of Volume IX, Hydrology, will be available in a few more weeks.

Candidates sought for top technical research position--Applications are invited for the newly created position, Director of Research and Development, Engineering Research and Development Laboratories, Fort Belvoir, Virginia. Candidates should have at least 15 years' experience in related work, with at least five years in administrative and technical charge of such work. Problems relating to civil, electrical, mechanical, and military engineering, physics, and physical and organic chemistry are involved, and liaison on high levels in the Armed Services, industrial and educational research organizations, and scientific and technical societies must be maintained. The salary will be $12,500 per year. Applications and inquiries should be addressed to the Commanding Officer, Engineering Research and Development Laboratories, The Engineer Center, Fort Belvoir, Virginia.

Proceedings of the Second International Conference on Soils Mechanics and Foundation Engineering--The proceedings from this International Conference held in The Hague, The Netherlands in June, 1948 are now available. The main proceedings contain six volumes, with a seventh in prospect if sufficient orders are received. Another volume relating to developments in Germany since 1939 is available separately. Inquiries concerning the seven volumes should be addressed to: Secretary, Second International Conference on Soil Mechanics and Foundation Engineering, Oostplantsoen 25, Delft, The Netherlands. Inquiries concerning the German papers should be addressed to: Library, Graduate School of Engineering, Harvard University, Cambridge 38, Massachusetts.

Sixth International Congress and Exhibition of Photogrammetry--The Sixth Congress and Exhibition was held at Scheveningen, The Hague, Netherlands, September 1-10, 1948, with 325 delegates and guests from 22 countries. Eleven delegates and two guests attended from the United States. Oliver S. Reading (who was Chairman of the delegation) and George H. Harding were representatives of the American Geophysical Union.

New Swedish geophysical journal--The Swedish Geophysical Society has recently completed plans for the publication of a new quarterly geophysical journal to be called Tellus. C.-G. Rossby is the editor. The first issue will appear in early March and will include a report by H. Petterson on the Albatross oceanic expedition, meteorological papers by T. Bergeron, E. Palmén, and A. Nyberg, and a report on recent ionospheric measurements in Lappland by O. Rybeck. Publication of papers and reports will be in English, French, and German, and papers on geophysics are invited from all countries.

The publication is made possible through the aid of a grant from the Swedish Government. The size will be 179 × 250 mm, with each issue containing 48 to 64 pages. Communications relating to subscription and manuscripts should be addressed to Editor of Tellus, University of Stockholm, Stockholm 12, Sweden.

Study of the subsidence of Terminal Island--A study of the causes of the subsidence of Terminal Island, Long Beach Harbor, California [see Trans., v. 29, pp. 17-26] is being made by the Stanford Research Institute with the hope that recommendations may be made for the solution of the difficulty.

Norwegian-Swedish-British Antarctic Expedition--Final plans are being formulated for an international expedition to Queen Maud Land under the leadership of Harald U. Sverdrup of the Norwegian Polar Institute. The party will embark in the fall of 1949 and be landed in January 1950 to spend two winters in the Antarctic. Aerial mapping will be carried out in the seasons 1950-1951 and 1951-1952, and the expedition will return to Europe in February 1952. The chief items to be investigated concern the Antarctic ice sheet, and the possibility that, like the ice in Arctic areas, it is currently retreating. Meteorological and geological investigations are also scheduled to be undertaken.

Annales Biologiques--Volumes 2 and 3 of this publication of the Conseil Permanent International pour l'Exploration de la Mer, covering the years 1942-1945 and 1946, respectively, were received in the United States in December 1948. In addition to biological studies of fishery problems, each volume contains descriptions of hydrographic conditions in the environment of the various North Atlantic fishing areas under the cognizance of the Council. Volume 1 (1939-1941) was distributed in March 1948. The publication is edited by H. Blegvad and is published by A. F. Høst in Copenhagen.

PERSONALIA

John A. Fleming, for many years Director of the Department of Terrestrial Magnetism, Carnegie Institution of Washington and now the Institution's Adviser in International Scientific Relations, was made a Commander in the Order of St. Olav by H. M. Haakon VI on September 7, 1948. He received his insignia on January 11, 1949 from the Norwegian Ambassador in Washington. The award is in recognition of Dr. Fleming's services to Norwegian scientists and to the Norwegian government.

Lawrence R. Hafstad, Executive Secretary of the Research and Development Board of the National Military Establishment has been named the first Director of the research unit of the Atomic Energy Commission charged with the problems of the development of atomic power.

C. L. Handa has been appointed Director of Irrigation Research of the East Punjab Government, Armritsan, India. Until recently, he was Director of Central Designs of the Punjab Irrigation Secretariat at Lahore.

Vincent F. Jennemann recently completed work for a Master of Science degree at St. Louis University, writing a thesis entitled A Meteorological Investigation of Microseisms at Corpus Christi, Texas. He is now engaged as a Research Computer in the Seismograph Department of the Sun Oil Company at Beaumont, Texas.

Walter D. Lambert retired January 18, 1949, following a year's recall to duty with the United States Coast and Geodetic Survey. His present address is Box 687, Canaan, Connecticut.

Thomas G. Thompson, Director of the Oceanographic Laboratories of the University of Washington, received the 1948 award of the Alexander Agassiz Medal. This medal is awarded annually by the National Academy of Sciences "for original contribution in the science of oceanography."

Merle A. Tuve, Director of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, was awarded the John Scott Award by Girard College for his outstanding contribution to the development of the radio proximty fuse during World War II.

Rollin T. Chamberlin, Professor of Geology at the University of Chicago died March 6, 1948 at the age of 67. He was born at Beloit, Wisconsin and obtained his baccalaureate degree from the University of Chicago in 1903 and his doctorate from the same university in 1907. His professional career began with the United States Geological Survey, following which he spent time in China and Brazil. He began his services on the staff on the University of Chicago in 1912, becoming full professor in 1923. He was a member of many scientific organizations, including the National Academy of Sciences. He had been a member of the American Geophysical Union since 1932.

Bent Skinner Drane, Consultant to and Deputy Member of the Panel on Hydrology of the Research and Development Board, died at his home in Chapel Hill, North Carolina on November 22, 1948. He was born at Edenton, North Carolina, September 9, 1881. He received his baccalaureate degree from the University of North Carolina in 1909. His professional career was devoted to diverse work, largely in the hydraulic and hydrologic fields, with the United States Geological Survey, the Bureau of Reclamation, private organizations, including his own consulting practice, and more recently with the National Resources Planning Board and the War Production Board. He retired from full time activity in 1947, and since that time had been engaged as a consultant to the Research and Development Board.

Daniel W. Mead, Professor Emeritus of Hydraulic and Sanitary Engineering of the University of Wisconsin, and consulting engineer died October 13, 1948 at the age of 86. He was born at Fulton, New York and received his baccalaureate degree from Cornell University in 1884. He began his professional career with a year's work on flood investigation work for the United States Geological Survey, subsequently working as engineer for municipalities, power companies, and construction companies, and soon entered upon an active consulting career which continued until his death. His teaching career at the University of Wisconsin extended from 1904 to 1932. His various writings are classics in the field of hydraulic engineering. He had been a member of the American Geophysical Union since the organization of the Section of Hydrology in 1930.

Americo R. Peracca, hydraulic engineer with the United States Geological Survey in California, died October 24, 1948 at the age of 41. He was born at Crockett, California, secured his baccalaureate degree from the University of California, and entered upon service with the United States Geological Survey in 1930. His professional career was devoted to the work of the Geological Survey in California and Venezuela, except the period from 1943 to 1946 during which he served in the Corps of Engineers, rising from second lieutenant to captain.

Gayle Scott, Professor of Geology at Texas Christian University died May 2, 1948 at the age of 53. He was born at Comanche, Texas, and received his baccalaureate and masters degrees from Texas Christian University in 1917 and 1920, respectively. He pursued graduate studies at the University of Colorado and the University of Chicago, and received his doctorate from Grenoble University in 1925. He had been a member of the staff of Texas Christian University since 1919, had been visting professor at the University of California, and had served on the Texas Bureau of Economic Geology.

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MINUTES OF EXECUTIVE COMMITTEE MEETING, AMERICAN GEOPHYSICAL UNION

Meeting of December 3, 1948

The meeting was called to order in the Tayloe Room of the Cosmos Club, Madison Place and H Street, N. W., Washington, D. C. at 13^{h}30^{m} by President Walter H. Bucher who expressed regret at the passing of our late President, O. E. Meinzer.

Present--Thirty-two persons were present, namely: L. H. Adams, K. Hilding Beij, Merrill Bernard, Walter H. Bucher, Wilbur S. Burbank, Horace Byers, Ralph E. Cleland, L. O. Colbert, F. L. Culley, H. N. Eaton, Jno. A. Fleming, Richard H. Fleming, W. F. Foshag, H. D. Harradon, H. W. Hemple, W. G. Hoyt, Earl Ingerson, W. C. Jacobs, H. Freeborn Johnston, David G. Knapp, W. D. Lambert, Ray K. Linsley, Jr., J. P. Marble, Martin A. Mason, G. Medina, Florence Robertson, Irwin Roman, James B. Small, Waldo E. Smith, H. T. Stetson, Walter D. Sutcliffe, and W. T. Thom, Jr. The following were excused because of absence from the city or for other reasons: Robert Balk, Arthur Bevan, J. Bjerknes, Detlev W. Bronk, Perry Byerly, J. E. Church, Ernst Cloos, R. C. Gibbs, M. King Hubbert, C. O'D. Iselin, George F. McEwen, A. G. McNish, W. A. Noyes, Edw. H. Smith, V. C. Stechschulte, Lorenz G. Straub, H. U. Sverdrup, F. J. Veihmeyer, and Howel Williams.

Approval of Minutes--The minutes of the Executive Committee meeting on April 24, 1948, as published in the August 1948 issue of the Transactions, pages 589 to 593, were approved.

General Secretary's Report

Executive Committee--The following changes in the membership of the Committee have occurred since the meeting of April 24, 1948. Walter H. Bucher was designated President of the Union by mail ballot of the Executive Committee to succeed Oscar E. Meinzer, deceased. Merrill Bernard, C. O'D. Iselin, and Howel Williams have become members by virtue of election to offices in Associations of the International Union. R. E. Cleland of Indiana University, the new Chairman of the Division of Biology and Agriculture of the National Research Council, replaces J. S. Nicholas. J. B. Small replaces H. F. Johnston as Chairman of the Standing Committee on Membership; H. F. Johnston retains his membership as last past president of the Section of Terrestrial Magnetism and Electricity. H. U. Sverdrup has resigned as Vice-President because of his return to Norway; he remains a member of the Executive Committee, as long as he is a citizen of the United States, as he is last past president of the Section of Oceanography and also President of the Association of Oceanography of the IUGG.

Office Personnel--Mrs. M. H. Salm has been appointed Clerk-Typist to succeed Mrs. M. J. Horan who resigned October 10, 1948.

Finances--A report of the Committee on Audit covering the detailed financial statement as of June 30, 1948, appeared in the December 1948 Transactions, pages 944 to 946. The cash balance as of November 30, 1948, excluding investments was $8937.57.

The grant of $3000 from the Geological Society of America for the calender year of 1948 was all received before July 1 and thus appears in the audited statement for June 30, 1948. According to unofficial word, a re-application for a grant for 1949 has been declined.

According to past instructions of this Committee, receipts from Life Memberships and other similar funds have been invested in Series F Government bonds. These bonds bear about 2 1/2 per cent interest, not compounded, over a period of 12 years; but in case they must be cashed before maturity, the interest rate is substantially reduced. Building and loan associations, with federal insurance on deposits up to $5000, are offering three per cent interest with the advantages that the interest is compounded semi-annually and that withdrawal may be made at any time without sacrificing this rate. A motion to authorize investment of permanent funds of the Union in such an association will be introduced under new business.

At the April meeting of this Committee the report of the Committee on Budget carrying a recommendation for an increase in dues was accepted. Approval of a change in the Statutes and By-Laws to implement this is required at this meeting. The Committee on Statutes and By-Laws has been requested to make an appropriate recommendation.

Membership--Despite the interruption of work of the Membership Committee caused by changes in its personnel, our membership has continued to grow. Following is a summary since April 16, 1948:

Members, April 16, 1948	4290	
New members	234	4524
Resignations	23	
Deceased	11	
Inactive	3	
Dropped for non-payment of dues	100	
Duplications, new member lists	3	140
Members, November 26, 1948		4384
Net increase since April 16, 1948		94

The following deaths have been reported since April 16, 1948: Emil J. Reimann, March 31, 1947; J. B. Brown, January 7, 1948; Donald G. McKeever, February 5, 1948; Charles R. Hedke, March 11, 1948; Isidore J. Broman, March 24, 1948; Oscar E. Meinzer, June 14, 1948; Harold W. Murray, June 15, 1948; François E. Matthes, June 21, 1948; Frank Rieber, June 30, 1948; Ralf R. Woolley, June 1, 1948; and Brent S. Drane, November 22, 1948.

The Committee on Membership has been reorganized. H. F. Johnston found it necessary to retire from the Chairmanship and J. B. Small has been appointed in his place. Present members of the Committee are T. S. Austin, F. M. Byers, H. Freeborn Johnston, R. K. Linsley, Jr., L. M. Murphy, and A. M. Piper.

W. C. Jacobs has suggested an arrangement for student membership and for student chapters.

We now have three corporation members as a result of the activity of the Subcommittee on Corporation Membership of which Irwin Roman is Chairman. This field seems to offer considerable opportunity in the way of financial support.

Administration of the Union--The Union was faced with a critical situation on June 14, 1948, by the sudden death of President Meinzer. This was complicated by the absence of the Vice-President from the country. The Committee on Nominations was requested to prepare a list of names for action by the Executive Committee. Chairman Macelwane held a meeting of the Committee in Washington soon thereafter to which all members of the Executive Committee within reach were invited. From the list of names proposed by the Committee, the Executive Committee by letter ballot designated Walter H. Bucher as President to June 30, 1950.

We now meet a similar situation in the resignation of Harald U. Sverdrup from the Vice-Presidency. The Committee on Nominations has been requested to present a list of nominees for action by the Executive Committee.

As there is no possibility at present of securing office space in the National Research Council building, your officers will request the Carnegie Institution of Washington to continue the present arrangements for another year.

National Research Council--It has been pointed out that under the Statutes of the National Research Council the Chairman is ex officio a member of all the committees of the Council. There is, however, no provision in our Statutes to this effect so the Committee on Statutes and By-Laws has been requested to bring in an amendment to rectify the matter.

The Council has continued the provision in its budget of a grant of $400 to the Union. In addition a grant of $300 was made to help defray the expenses of the Executive Secretary in attending the Eighth General Assembly of the International Union at Oslo.

The Council designated all citizens of the United States who attended the Eighth General Assembly of the International Union at Oslo (except guests) as delegates to the meeting.

Meetings--The Committee on Meetings has set April 20 to 22 as the dates for the Thirtieth Annual Meeting. A suggestion by H. H. Hess that papers having interest to several Sections be grouped for presentation at joint sessions of Sections has been passed on to the Chairman of the Committee.

The Twenty-Third Regional Meeting is to be held in Los Angeles in February 1949, and the Twenty-Fourth in Denver in April 1949.

Publications--The Transactions are being issued in editions of 5200 copies of about 150 pages each. A second part of about 80 pages containing the list of members was issued in August. The December issue, now in press, will contain 194 pages, the extra length being due to a posthumous paper by Robert E. Horton and the annual index.

The Editorial and Publication Committee has practically completed the index for the first 25 years of the Transactions. A motion regarding publication of this index will be introduced in this meeting by the Chairman of the Committee.

American Geological Institute--The President appointed Ernst Cloos and W. T. Thom, Jr., as interim directors to represent the American Geophysical Union at the organization meeting of the Institute this fall. Directors are to be appointed for two year terms on the staggered basis, with appointment to a one-year term and a two-year term in the first instance. The Executive Committee at this meeting should decide on the method of apppointment and should provide for the first appointments.

UNESCO--The Pacific Regional Conference on UNESCO was held in San Francisco on May 13 to May 15, 1948. Our representatives were Perry Byerly, R. E. Fuller, V. P. Gianella, J. C. Stevens, and C. K. Wentworth. T. G. Thompson and F. J. Veihmeyer were also designated but were not able to attend. A brief report on the meetings was published in the Transactions of August, page 596.

Delegates to Meetings--L. G. Straub and W. C. Lowdermilk were designated to represent the Union at the centennial celebration of the French Society of Civil Engineers. Dr. Lowdermilk was unable to attend.

G. H. Harding and O. S. Reading were designated representatives to the Sixth International Photogrammetry Congress and Exhibition at The Hague, Netherlands, September 1 to 10, 1948.

S. W. Lohman was designated representative to the Inter-American Conference on Conservation of Renewable Natural Resources held at Denver, September 7 to 20, 1948.

G. Medina, Chairman of the Committee on Surveys and Maps, was designated representative to the Fourth Pan-American Consultation on Cartography at Buenos Aires, October 15 to November 14, 1948. H. W. Hemple was designated alternate.

K. HILDING BEIJ, General Secretary

Action on the General Secretary's Report--The report was accepted.

Reports of Standing Committees

Statutes and By-Laws--Chairman Harradon reported that the only change necessary in the Statutes and By-Laws [Trans., v. 26, pp. 173-177, August 1945] to permit an increase in dues in accordance with the action of the Executive Committee on April 24, 1948 [Trans., v. 29, p. 594, August 1948] is as follows: In By-Law 2, change $5 in the second line to $7 so that the first part of By-Law 2 shall read "(2) Members of the Union, in classes (a) and (d) of Article 3 of the Statutes, shall pay dues not to exceed $7 for each calendar year, the amount for each year to be fixed by the Executive Committee of the Union; . . . ." the By-Law to remain otherwise unchanged. This amendment was approved, and it was voted that it should be submitted to the membership for action by mail ballot early in 1949.

The Chairman of the Committee opened discussion regarding the Chairman of the National Research Council who is ex officio a member of all committees of the Council under the Statutes of the Council, but no statement of this appears in our Statutes. Recognizing that the Statutes of the Council take precedence over our Statutes, it was agreed that no amendments to our Statutes is necessary.

Membership--Chairman Small outlined briefly the plans of the Committee, now being implemented, to carry on the work of the Committee.

Corporation Membership--Chairman Roman reported that work is progressing with regard to the solicitation of corporation membership, and that he has several hundred corporations in the list to write to. Only a few letters have gone out thus far; these have brought three favorable responses.

Meetings--Chairman Marble reported concerning meetings as follows: The Twenty-Ninth Annual Meeting was held as scheduled in Washington, D. C. on April 21-23, 1948. A summarized report thereof has appeared in the Transactions [pp. 429-448, June 1948].

The Twenty-Third Regional Meeting will be held at the University of California, Los Angeles, California on February 4-5, 1949. The Sections of Hydrology and Meteorology will definitely meet. Opportunity for the presentation of papers in other fields will be available.

The Twenty-Fourth Regional Meeting will be held in Denver, Colorado, April 26-27, 1949, jointly with the Western Snow Conference. The Section of Hydrology alone plans to meet, but related papers will be welcome.

The Thirtieth Annual Meeting will be held in Washington, D. C. on April 20-22, 1949, using various auditoria. A symposium joining Oceanography, Hydrology, and Meteorology is planned for this meeting.

It is planned to hold the Thirty-First Annual Meeting in Washington, D. C., during the last week in April or the first week in May 1950. It has become essential to set up fairly definite dates at least this far in advance to provide for proper arrangements for symposia, and to ensure that adequate meeting rooms are available.

Approval was given to the four meetings in prospect and their dates, leaving the Committee latitude with regard to the dates for the Thirty-First Annual Meeting, with dates to be quite definitely set as soon as possible subject to Executive Committee approval at the time of the Thirtieth Annual Meeting.

With regard to regionalization of the Union, Chairman Marble reported that it has not proved possible to make much advance in such plans due to lack of response from the Section Officers and others concerned, with the exception of those connected with the Section of Hydrology. A considerable difference in the geographical distribution of various sections and the presence or absence of other facilities for papers and discussions of interest to various sections appears to be the underlying cause of this lack of interest. It is to be hoped that more vigorous steps can be taken to ensure that members of the Union who are unable to come to Washington may be assured of the opportunity of holding meetings in other places at intervals under Union auspices.

There was considerable interest in and discussion of this, reference being made to the report submitted by the Section of Hydrology to the Executive Committee on November 28, 1947 [Trans., v. 28, pp. 147-148, February 1948] and it was voted that a Committee on Regionalization of the Executive Committee be designated by the President. This Committee is to work closely with the Committees on Meetings and on Membership, with a report to be presented by April 23, 1949 (date tentatively set as the next meeting of the Executive Committee).

President Bucher urged that members of the Executive Committee make special effort to be present at the Business Meeting of the Union, held near the close of the Annual Meeting each year, and that they gather in the forward seats of the meeting room. He also urged that arrangements of the programs on vital topics should be begun a year or two in advance.

Editorial and Publication--Chairman Beij reported that a new edition of "Suggestions to Authors" is about complete and will be published in the February issue of the Transactions. The "Suggestions" have been condensed to two pages.

The indexing of the first 25 years of the Transactions is now about complete. A recommendation for financing the publication will be made by the Committee on Budget.

Budget--Chairman Eaton reported that the Committee on Budget has conferred with the General and Executive Secretaries of the Union and made one recommendation to the Executive Committee, relating to financing the publication of the Index to the Transactions of the Union through 1944. In view of the great need for and the value of the proposed Index, the Committee on Budget recommends that the General Secretary be authorized to make an initial outlay of not in excess of $1000 for the preparation and publication of this Index, and that a sales price be established which it is estimated will liquidate all costs of publication within a reasonable period--say, three years. This was approved.

Nominations--Chairman Macelwane was absent but called by telephone from St. Louis advising that he had just returned from a protracted trip and found the letter regarding the vice-presidential vacancy awaiting him, and requested the guidance of the Executive Committee. It was agreed that the preferential ballot, providing three nominees with space for a fourth to be written in such as was used in the selection of a president, be approved.

Audit--Chairman McNish was absent. The report of the Committee was published in the Transactions of December 1948 [pp. 944-946] and was read in part. It was approved.

Reports of Special Committees

Cooperation with International Commission for Study of Tidal Waves--Chairman Mason recommended that the name be changed to Special Committee for the Study of Tsunamis. This was approved.

Cosmic-Terrestrial Relationships--Chairman Stetson called attention to the report of the Committee that had been published [Trans., v. 29, pp. 436-440, June 1948] and made a brief report of subsequent activities.

Award of the William Bowie Medal--Chairman Colbert advised that suggestions and recommendations for the next medalist are invited. The first ten awards were as follows.

Number	Year	Recipient
First Award	1939	William Bowie (deceased)
Second Award	1940	Arthur Louis Day
Third Award	1941	John Adam Fleming
Fourth Award	1942	Nicholas Hunter Heck
Fifth Award	1943	Oscar Edward Meinzer (deceased)
Sixth Award	1944	Henry Bryant Bigelow
Seventh Award	1945	Jakob Aall Bonnevie Bjerknes
Eighth Award	1946	Reginald Aldworth Daly
Ninth Award	1947	Felix Andries Vening Meinesz
Tenth Award	1948	James Bernard Macelwane

Surveys and Maps--Chairman Medina who was the AGU representative at the Fourth Consultation of the Commission on Cartography, held in Buenos Aires, October 14 to November 3, 1948, reported on the Consultation as set forth in Appendix 1.

Chairman Medina also mentioned his desire to present an exhibit of maps at the Annual Meeting next spring, and was advised that exhibit space would be available.

Reports of Sections

Geodesy--President Hemple advised that one of the outgrowths of the Oslo meeting is the plan to work out a common datum for the triangulation net of Western Europe, the prime need of which is for navigational use.

Meteorology--President Byers repeated the plan of the Section to hold a meeting on the West Coast in February, and stated that the American Meteorological Society will meet with the Section at the Thirtieth Annual Meeting in Washington.

Reports of Divisions of National Research Council

Physical Sciences--In the absence of Chairman Gibbs, L. H. Adams advised that the question has been raised whether the Physics of the Earth, Volume VII, The Internal Constitution of the Earth, should be revised and republished, or simply republished, and that the idea of revision before publication was preferred.

Reports on Affiliation with Other Organizations

American Geological Institute--W. T. Thom, Jr., one of the two interim directors from AGU appointed by the President reported as set forth in Appendix 2.

With regard to the procedure for the designation of the AGU directors of the American Geological Institute, it was moved by L. H. Adams and passed that, in the absence of any pertinent provision in the Statutes and By-Laws, it is the sense of the Executive Committee that the designation of the Directors of the American Geological Institute from the American Geophysical Union be made by the President of the Union.

New Business

Affiliation with the Geological Society of America--The question was raised whether the American Geophysical Union should take steps to become one of the societies associated with the Geological Society of America "for the purpose of cooperation in . . . meetings, publications, and other ways . . ." Inasmuch as this bears closely upon regional meetings, it was referred to the newly created Committee on Regionalization.

Investment of Life Membership Payments and Other Special Funds--It was pointed out in the General Secretary's report that depositing in federally insured building and loan associations, an interest rate of three per cent compounded semi-annually may be secured. Accordingly it was authorized that the General Secretary be empowered to invest funds of the AGU in reputable building and loan associations carrying federal insurance on deposits, provided that the amount in any association does not exceed the insurance limitations, and provided further that the approval of the Budget Committee be secured in advance.

Student Membership and Student Chapters--W. C. Jacobs recently pointed out a need for a student membership and a probable need for the establishment of student chapters on some campuses. It was approved that the problem be studied and that a special committee be appointed for this purpose and to report.

Funds to Attend International Meetings--W. D. Lambert mentioned the desirability of the attendance by the Executive Secretary at the Triennial Assemblies of the International Union of Geodesy and Geophysics and moved that the matter of establishing an annual reserve to provide a fund for such attendance be referred to the Committee on Budget. This was approved.

Elections--It was pointed out that 1950 is the year of the triennial elections, and that in this connection it is essential that sections reactivate their Committees on Nominations at a very early date, and that all Committees on Nominations (including the Committee of the Union) get machinery under way early in 1949 in order that the schedules or calendars set forth in the Transactions of December 1946 [v. 27, pp. 910-914] will be maintained.

Visit of G. E. R. Deacon to the United States--It was announced that word has been received that G. E. R. Deacon, British oceanographer, will visit the United States briefly following the Pacific Science Congress in New Zeland. He will be here in the late winter or early spring of 1949.

Adjournment--The meeting was adjourned at $16^{h}42^{m}$.

K. HILDING BEIJ, General Secretary
WALDO E. SMITH, Executive Secretary

APPENDIX 1--REPORT ON THE FOURTH CONSULTATION OF THE COMMISSION ON CARTOGRAPHY AT BUENOS AIRES

The Fourth Consultation of the Commission on Cartography of the Pan American Institute of Geography and History was held in Buenos Aires, Argentina, October 14 to November 3, 1948.

Approximately 200 delegates, advisors, and observers were present, representing the Pan American States, Canada, and scientific organizations such as the International Union of Geodesy and Geophysics, the International Society of Photogrammetry, International Hydrographic Bureau, the International Civil Aviation Organization, the American Society of Photogrammetry, the American Congress of Surveying and Mapping, and the American Geophysical Union. Special guests included Professor Poivilliers of France, Professor Santoni of Italy, and Captain Guillen of Spain.

The conferences were held in the new building of the Faculty of Law and Social Sciences which also housed the cartographic exposition. This imposing structure was ideal for a conference of this nature.

The cartographic and surveying exposition was one of the most comprehensive ever assembled. Charts of all types were exhibited and methods and techniques illustrated in detail. European surveying and photogrammetric equipment of the latest design was displayed and explained by experts. It is regretted that our manufacturers of surveying, mapping, and reproduction equipment, all of whom had been invited to take an active participation, did not avail themselves of this opportunity to display the excellent equipment manufactured in the United States.

The United States mapping agencies can well be proud of the exhibit they sent to Buenos Aires. It is planned to have this same exhibit on display in Washington upon its return from Argentina. The time and place will be announced in the press and through other mediums. Map makers and map users should plan to see this outstanding exhibit of American cartography.

Committees dealing with geodesy, topography and photogrammetry, hydrography, special maps, and geomagnetism and seismology, discussed problems of common interest to the nations represented and passed resolutions which, if fully carried out, will insure the results of future efforts to be of the highest order. Outstanding among these will be the establishment of a common datum for South America. Resolutions adopted at this conference will be published at a later date.

The next meeting of the Commission on Cartography is scheduled to take place in Santiago, Chile, in August 1950.

G. MEDINA

APPENDIX 2--REPORT TO THE AMERICAN GEOPHYSICAL UNION ON THE ORGANIZATION OF THE AMERICAN GEOLOGICAL INSTITUTE

The meetings called to complete the organization of the American Geological Institute were held as planned on November 15 to 16, 1948, and were attended by representatives of all 11 of the Founder Societies, including Ernst Cloos and W. T. Thom, Jr., delegates of the American Geophysical Union.

The matters of Institute policy, program, and finances were extensively discussed and developed, in part by working committees on Public Relations, Government Relations, Education Publication, Personnel, Research Information, and Finances.

A. I. Levorsen was elected President of the Institute; W. B. Heroy, Vice-President; and Earl Ingerson, Secretary-Treasurer. The several Founder Socieites (unless they had already done so) were requested to designate two directors as Institute Council-members, one for one year and one for two years, initially, with each subsequent appointment to be for two years.

The Standing Committees of the Institute are to be appointed by the President, with guidance by ballot nominations from the Council members, and the Institute's Executive Committee was instructed to check on the men possibly available to become Institute Executive Secretary, while simultaneously working with the Finance Committee on establishing an adequate Institute Budget.

W. T. THOM, JR.

Transactions, American Geophysical Union Volume 30, Number 1 February 1949

National Research Council
AMERICAN GEOPHYSICAL UNION
1530 P Street, N. W.
Washington 5, D. C.

SUGGESTIONS TO AUTHORS ON PREPARATION OF MANUSCRIPTS FOR THE TRANSACTIONS OF THE AMERICAN GEOPHYSICAL UNION

General--Contributions in English on geophysical subjects for publication in the various departments of the Transactions are welcomed from members and non-members. All contributions are subject to approval and editing by the Editorial and Publication Committee. The AGU reserves the right to reject any contribution, but it assumes no responsibility for statements and conclusions of contributors. Papers dealing mainly with engineering, climatological, and similar applications, involving no new principle, or those that are just a reworking of material previously published, or that advocate personal interests, will not be accepted. However, a liberal attitude will be taken regarding papers on controversial subjects, or papers attempting to establish some new idea, even though apparently counter to commonly accepted views, as long as the logic is sound and clear, and the fact that there is controversy is evident. All controversy must be objective.

Acceptance of papers for presentation at meetings of the Union or its Sections does not imply acceptance for publication, but it is assumed that such papers will be offered in the first place for publication in the Transactions, unless other arrangements are made at the time of submission. It is against the policy of the Union to publish papers simultaneously with or subsequent to publication elsewhere.

It is the Author's responsibility to prepare his material in logical and attractive form, so that it may be read by a specialist in that field without need of interpolating the author's intentions. To this end, and to facilitate editing and preparation for publication, authors are requested to comply with these suggestions. Manuscripts grossly at variance with these suggestions will be returned for revision.

Accepted contributions will be scheduled as nearly as possible in order of receipt, subject to maintaining a reasonable balance in each issue among the fields of geophysics as represented by the Sections of the AGU.

Aids in preparation of manuscript--In general, the Editors will adopt the conventions of the University of Chicago Press as published in "A Manual of Style." In editing, every effort will be made to preserve the author's style, bearing in mind the fact that certain conventions are essential in any serial journal. The following texts are recommended:

ALLBUTT, T. CLIFFORD, Notes on the composition of scientific papers, Macmillan and Co.
TRELEASE, S. F., and YULE, E. S., Preparation of scientific and technical papers, Williams and Wilkins Company.
WOOD, F. M., and LANE, B. H., Suggestions to authors, Superintendent of Documents, Washington 25, D. C.

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